ILLINOIS STATE WATER SURVEY
ATMOSPHERIC SCIENCES SECTION

EVALUATION OF POTENTIAL BENEFITS OF WEATHER MODIFICATION ON WATER SUPPLY

by

F. A. Huff
Principal Investigator

TECHNICAL REPORT NO. 1
ILLINOIS PRECIPITATION ENHANCEMENT PROGRAM
PHASE 1

April 1, 1973

To

Division of Atmospheric Water Resources Management
Bureau of Reclamation
U. S. Department of Interior

Contract 14-06-D-7197
September 1, 1971

DATE DUE			

Huff, F. A.
EVALUATION OF POTENTIAL BENEFITS OF WEATHER MODIFICATION ON WATER SUPPLY; TECHNICAL REPORT NO. 1

ILLINOIS STATE WATER SURVEY
ATMOSPHERIC SCIENCES SECTION

EVALUATION OF POTENTIAL BENEFITS OF WEATHER MODIFICATION ON WATER SUPPLY

by

F. A. Huff
Principal Investigator

TECHNICAL REPORT NO. 1
ILLINOIS PRECIPITATION ENHANCEMENT PROGRAM
PHASE 1

April 1, 1973

To

Division of Atmospheric Water Resources Management
Bureau of Reclamation
U. S. Department of Interior

Contract 14-06-D-7197
September 1, 1971

CONTENTS

Page

ILLUSTRATIONS

TABLES

ACKNOWLEDGMENTS

This research was carried out under the general direction of S. A. Changnon, Jr. , Head, Atmospheric Sciences Section. Elmer Schlessman was primarily responsible for much of the data analysis and supervision of subprofessional personnel. Arthur Sims accomplished the computer programming required for various phases of the work, and assisted in the analysis in the early phases of the study. Linda Schmidt and Nancy Wallick , student assistants, accomplished much of the large amount of routine data analysis required with the various analyses.

Mark Edgington, a graduate student in economics at the University of Illinois, carried out a literature survey that was useful in efforts to evaluate potential economic benefits to water supply in Illinois. John Brother provided valuable assistance in the drafting of report illustrations. Marvin Clevenger supervised the machine processing involved in the project.

John Stall, Julius Dawes, Richard Schicht, and W. J. Roberts of the Water Survey's Hydrology Section provided helpful advice and suggestions in certain phases of the work, particularly in efforts to assess potential economic benefits, needs and applicability of weather modification to augment water supplied in Illinois, and potential erosion and sedimentation that might be associated with weather modification.

ABSTRACT

An investigation was made of the potential benefits of seeding-induced increases in runoff on alleviation of surface water shortages in Illinois. Runoff and weather data for 14 basins of various sizes and locations and with records of 30 years or longer were used to develop basin equations relating runoff to antecedent runoff indices , various precipitation parameters, and mean temperature. Hypothetical seeding-induced increases in precipitation were then used with the appropriate basin equation to obtain an estimate of average runoff increases in the cold season (October-March), the warm season (April-September), and two subseasons, December-March and July-August. This was done for all seasons combined, seasons having near-normal to below-normal runoff, and seasons with below-normal streamflow. Results indicated that . seeding could result in substantial increases in runoff during near-normal to slightly below-normal years. However, substantial runoff would be difficult to achieve in drought years unless exceptional rainfall increases could be achieved. Previous hydrologic studies at the Water Survey indicated that major benefits to water supply in Illinois would only result if substantial gains could be made in moderate to severe drought conditions. Consequently, it appears that the major beneficiary of weather modification in Illinois would be agriculture, and that future efforts should be concentrated on weather modification applications in the growing season.

INTRODUCTION

This study involved an evaluation of the potential benefits of precipitation augmentation on water supplies under typical midwestem conditions. In the first phase, Illinois data were employed to assess 1) the general magnitude of water-supply augmentation that could be realized under various assumed seeding-induced increases in natural precipitation, and 2) the relative effects of climatic, physiographic, and geomorphic features upon seeding-induced benefits. Standard mathematical and statistical techniques were used to derive regression equations that reflect the importance of various meteorological and hydrological factors in defining basin runoff. A total of 14 Illinois basins with continuous runoff records for a minimum of 30 years were selected to provide a measure of potential water-supply benefits under various basin characteristics. Particular emphasis was placed upon the southern and south central parts of the state where surface waters are the primary source of water supply. Seeding-induced precipitation would be most beneficial in the southern one-third of the state from both water supply and agricultural considerations.

Next, an investigation was made of the frequency of serious water shortages in Illinois with major emphasis on impounding reservoirs. This was done to obtain an estimate of the potential economic benefits from weather modification. Limited consideration was given also to the consequences of additional erosion and sedimentation that might be induced by rainfall augmentation.

ANALYTICAL TECHNIQUES USED IN ESTIMATING SEEDING-INDUCED RUNOFF

Stepwise correlation and regression techniques were used in deriving equations which relate basin runoff to antecedent indices, precipitation parameters, and temperature conditions. The antecedent indices employed were runoff and rainfall in the month preceding the period of interest. Mean seasonal temperature for winter and summer were used as temperature variables. Precipitation parameters included seasonal totals, sub-seasonal amounts, monthly totals, maximum monthly precipitation, snowfall (cold season), and number of days with precipitation. This provided a group of 15 variables in the cold season (October-March) and 14 variables in the warm season (April-September) for relating to the seasonal runoff.

Although the best correlator with seasonal runoff is usually total seasonal precipitation, it is obvious that the nature and magnitude of the seasonal runoff is also dictated by how this total precipitation is distributed throughout the season. Thus, although the various precipitation parameters are not strictly independent in the statistical sense, combinations of these distribution measures were considered both desirable and necessary to reflect realistically the hydrological-meteorological relationships. That is, within the limitations of available data one must employ the best means of assessing the conversion of the meteorological input (precipitation) into the hydrological output (runoff) which determines available surface water supplies.

In the Illinois study, the year was divided into two basic seasons. The cold season was defined as the months from October through March and the warm season as the April-September period. Shallow-aquifer replenishment is favored in the cold season, particularly in the December-March period which was used in sub-season analyses (Hudson and Roberts, 1955). Also, special analyses were performed for the July-August period when evapotranspiration losses are normally greatest.

For the cold and warm seasons, several types of basin regression equations were developed and tested for optimum applicability in the water supply study. . Initially, for each basin an equation was determined based upon data for all years of record. Testing indicated that the standard error of the regressions is usually reduced by insignificant amounts after four "independent" variables have been introduced into the basin equations. Consequently, basin equations throughout the study were usually restricted to this number of variables.

Basin equations were developed also for the data stratified according to the upper, middle, and lower one-third of the seasonal runoff. Unfortunately, with this grouping, the data sample for equation derivations was too small to obtain stable relationships in the warm season, but relatively high correlations were maintained with most basins in the cold season. However, analyses performed on those years in which the runoff was near normal to below normal (lower 2/3 of seasonal runoffs) provided equations which maintained a relatively high level of correlation in both seasons. These are years in which augmentation of water supplies through weather modification could be beneficial in the Midwest. Thus, increased precipitation in near-normal years could be used to increase the storage in impounding reservoirs below full capacity. During below-normal years when drawdown is occurring in many reservoirs, alleviation of the drawdown rate could lessen the probability of critical shortages if the precipitation deficiency became prolonged. In communities taking their water supplies directly from streams, increasing the base flow in below-normal years would again lessen the probability of critical shortages if the drought condition continued. Consequently, much of the analysis was concentrated on evaluation of seeding potential in near-normal to below-normal years.

Hypothetical seeding models were applied to each basin equation to provide an estimate of the additional runoff that would result from seeding-induced rainfall of 20%, which is considered an average seeding capability under favorable conditions (MacDonald, 1966). Constant-change seeding which assumes proportional increases in all major precipitation variables controlling the basin runoff was used in the study. Seeding increases were applied to actual precipitation occurrences in each year of record, similar to the method used in an earlier study of potential effects of weather modification on agriculture (Changnon and Huff, 1971).

This Changnon-Huff study indicated similar results when either constant-change or variable-change models were applied in the regional prediction equations to evaluate seeding-induced effects on crop production. The variable-change models, which alter the seeding-induced effect with varying amounts of natural daily precipitation, require much more time-consuming tabulation and analyses. This would greatly increase the labor involved in the runoff study in which the variable-change models would require the use of daily rather than monthly runoff analyses. In view of our experience in the agricultural study referenced above, the first-approximation goal of the water supply study, and the limited funds assigned to this particular investigation, it was decided to restrict the water supply evaluation to the use of constant-change models. In the Illinois study, emphasis was placed upon use of simple, relatively inexpensive techniques that would be readily adaptable to 1) various regions of the country, and 2) basins for which only standard climatological data and runoff are available.

In view of the existing uncertainties both in weather modification technology and in evaluation of the complex precipitation-runoff relationships, it was considered quite appropriate to undertake initially the above type of analysis to obtain first approximations of the magnitude of the potential seeding effect and how it might vary with such factors as climate, physiography, geomorphology, and size of watershed. In the future, more comprehensive studies may be justified in which more sophisticated methods, such as use of the Stanford Watershed Model (Crawford and Linsley, 1962), could be utilized for selected basins that reflect typical climatic and hydrologic conditions of a given region. The analytical results presented here are intended to provide information not only on the general magnitude of the weather modification effect, but to permit assessment of the relative importance of various factors that could be utilized in determining the type and extent of more refined analyses undertaken in the future.

BASIN BACKGROUND INFORMATION

Figure 1 shows the location, relative size, and shape of the 14 basins used in the study. Table 1 provides a general description of the 14 basins which includes area, period of continuous runoff records, geombrphic and physiographic classifications of each basin, the major water-supply source (surface, water, groundwater, or mixture), and general location within the. state. Figure 2 shows the location of the climatic stations which furnished precipitation and temperature data utilized in the water-supply analyses. Figure 3 is a map showing the location of the primary surface water and groundwater supplies. The most likely location of any major weather modification experiment in Illinois in the future would be the claypan soil region in the southern part of the state, with activities centered about Salem (SLM, Fig. 2).

Table 1. Study basins

Basin	Area (mi^2)	Continuous record (yrs)	Major water-supply source	Geomorphic type	State location
Sangamon	5120	1939-70	Mixture	Glacial Plain (2 stages)	East Central
Upper Kaskaskia	1980	1914-70	Mixture	Glacial Plain (2)	East Central-South Central
Big Muddy	785	1914-70	Surface	Glacial Plain (1)	South
Little Wabash	3111	1939-70	Surface	Glacial Plain (1)	Southeast
Skillet Fork	464	1928-70	Surface	Glacial Plain (1)	South
Embarras	1513	1914-70	Mixture	Glacial Plain (1, 2)	East
Spoon	1600	1914-70	Mixture	Glacial Plain (1)	Northwest
La Moine	1310	1921-70	Surface	Glacial Plain (1)	West
Green	958	1936-70	Ground	Fluvial-Lacustrine Plain (Glacial-Fluvial)	Northwest
Macoupin	875	1940-70	Mixture	Glacial Plain (1)	Southwest
Cache	243	1924-70	Mixture	Dome Uplift	Extreme South
Henderson Creek	428	1935-70	Surface	Glacial Plain (1)	Northwest
Vermillion (North)	568	1942-70	Ground	Glacial Plain (2)	East Central
Kishwaukee	1090	1940-70	Ground	Glacial Plain (2)	Extreme North

Physiographic regions

Springfield Plain - Embarras, Kaskaskia, Macoupin Creek, Sangamon (plus Bloomington Ridged Plain)

Mt. Vernon Hills (mostly claypan soils) - Little Wabash, Skillet Fork, Big Muddy

Shawnee Hills - Cache River. Galesburg Plain - La Moine, Spoon, Henderson Creek

Rock River Hills - Kishwaukee. Green River Lowland - Green River. Kankakee Plain - Vermillion

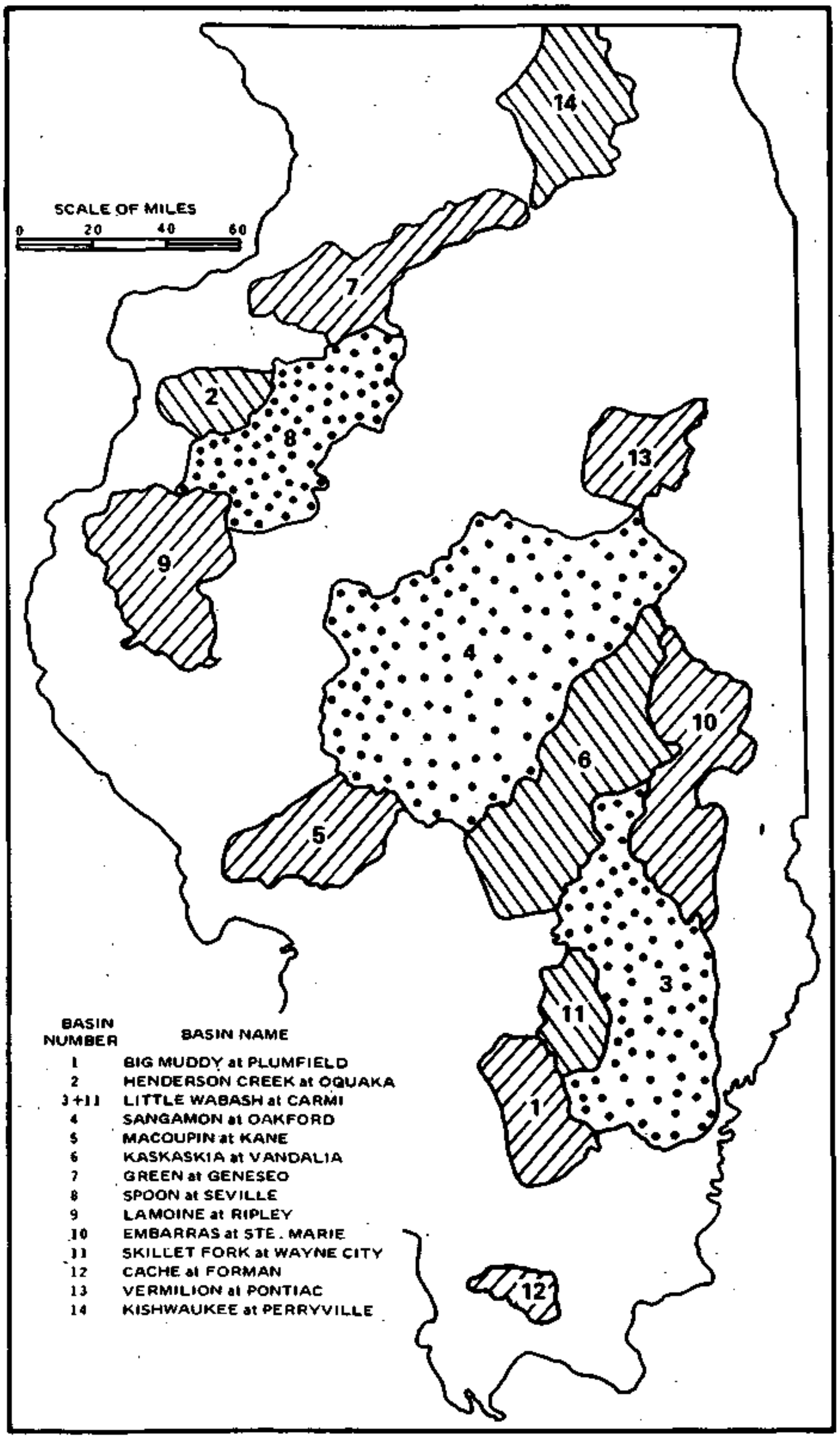

Figure 1. Basins Used in Water-Supply Study

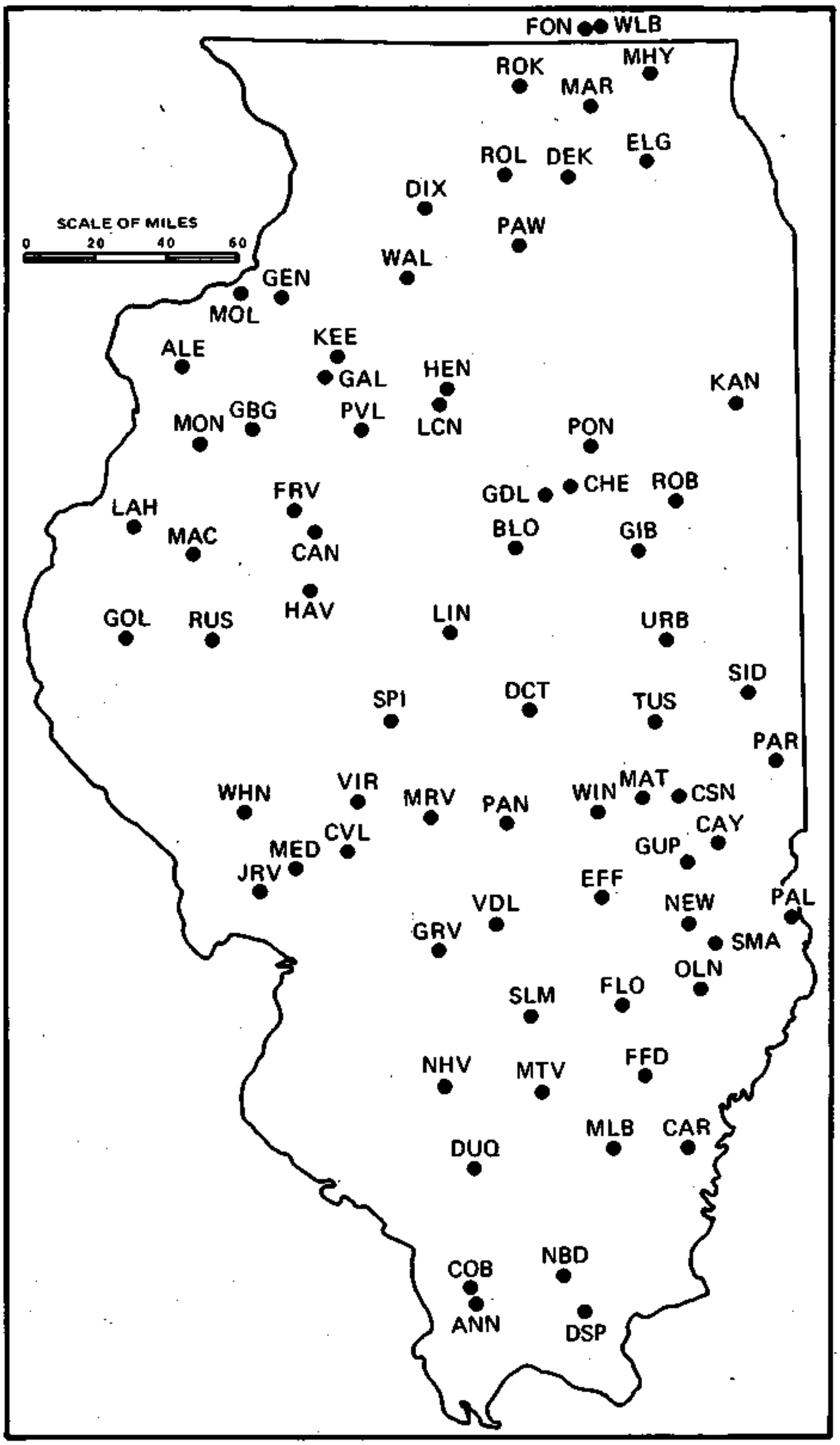

Figure 2. Climatic Stations Used in Water-Supply Study

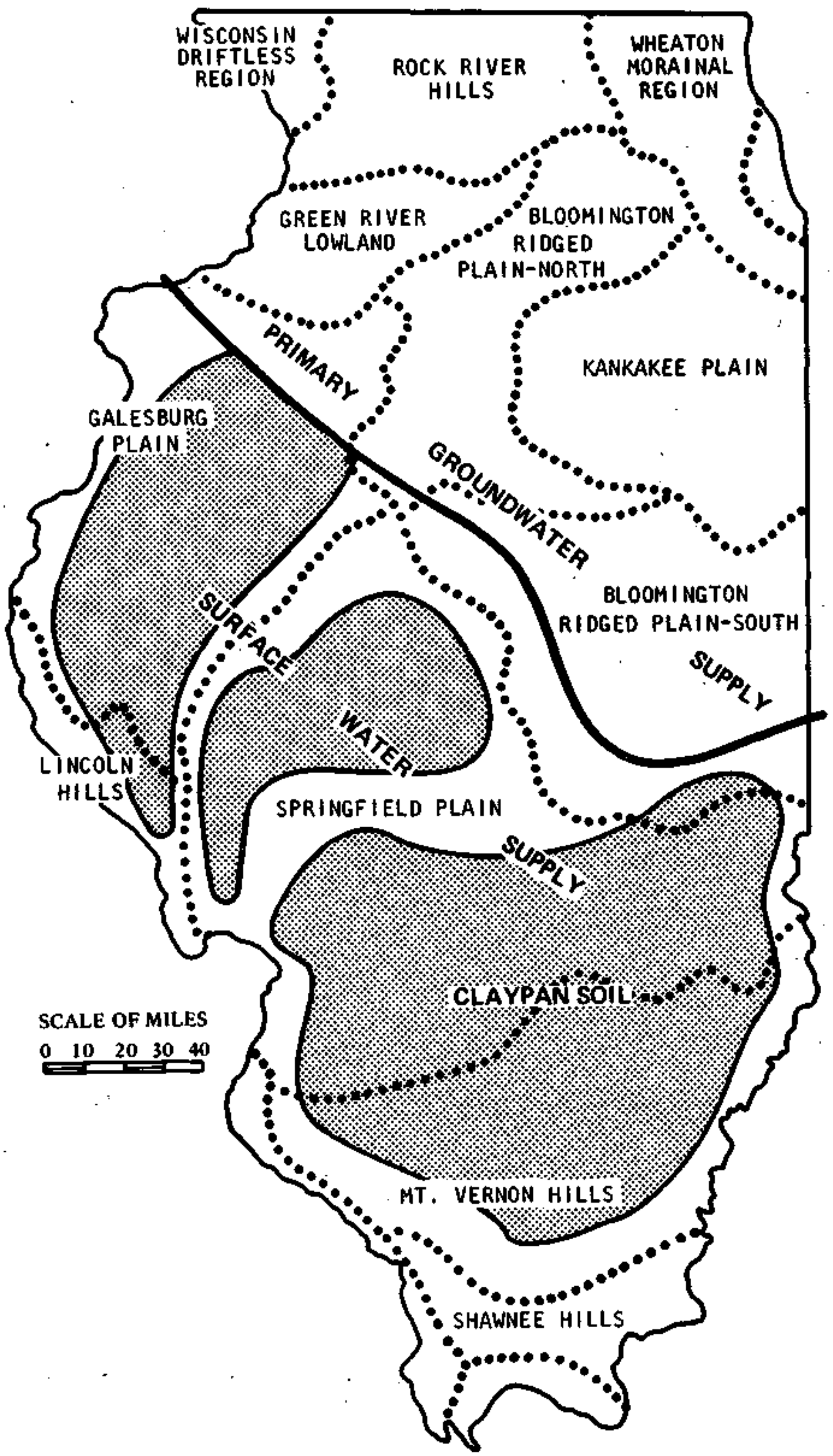

Figure 3. Physiographic and Primary Water-Supply Regions

Two basic properties useful in the evaluation of runoff-precipitation relations are the average seasonal runoff and precipitation for the basins being studied. These seasonal values are presented in Tables 2 and 3 for each of the 14 basins and seasonal periods employed in the study, based upon use of the periods of record shown in Table 1.

GROUPING OF BASINS FOR RUNOFF STUDY

Analyses were made to determine whether the 14 basins could be grouped according to their physical properties or climatic conditions. Examination was made of possible grouping according to physiographic regions, (Leighton, et al., 1948), geomorphic regions (Von Englen, 1942), a basin climatic index (Thornwaite, 19 31), and the general character of the soils. The runoff/rainfall ratio (R/P) and the Thornwaite climatic index (BCI) were used to characterize potential groupings. Huff and Changnon (1964) have shown the applicability of R/P values in characterizing basic runoff properties under low flow conditions. R/P was examined for average conditions during the period of basin records and for its modified value after applying the seeding models in the basin regression equations.

No type of grouping proved completely satisfactory. R/P values for the claypan soil region of southern Illinois were found to be very similar for the three basins completely (or nearly so) in that region (Big Muddy, Skillet Fork, Little Wabash) and for the Embarras with over 50% of its area in the claypan region. The Kaskaskia has very similar BCI and R/P values (Table 4) to those for the four basins grouped in the claypan region above, although only a small portion of its area is in that region.

The La Moine, Spoon, Henderson Creek, and Sangamon are located partly or entirely in regions depending primarily upon surface water supplies in the Galesburg and Springfield Plains. Their BCI and seasonal R/P values indicate a satisfactory grouping. The Cache Basin, located in the Shawnee Hills had unusually high BCI and R/P values which place it in a separate class from the other basins. The Green River, Vermillion, and Kishwaukee Basins are located in the primary groundwater area of Illinois. The Green and Kishwaukee compared closely in seasonal R/P values; the Vermillion departed somewhat from the others in seasonal R/P values but was very close to the Green River Basin in annual BCI and annual R/P values. Table 4 shows the annual BCI, annual R/P, and seasonal R/P values for the 14 experimental basins.

Table 2. Mean seasonal runoff

Basin	Oct.-March	Dec.-March	April-Sept.	July-Aug.
	Runoff (inches) for given season			
Big Muddy	7.05	6.22	5.00	0.79
Little Wabash	6.07	5.31	4.87	0.79
Skillet Fork	6.25	5.66	4.83	0.72
Embarras	5.69	4.90	4.93	0.79
Cache	10.13	8.93	6.56	0.78
Kaskaskia	4.92	4.18	4.76	0.81
Sangamon	3.66	2.96	4.77	0.97
Macoupin	3.34	2.72	4.17	0.85
Vermillion (North)	3.11	2.96	5.03	0.84
La Moine	3.31	2.67	4.51	0.99
Spoon	3.68	2.97	4.68	1.00
Henderson Creek	3.51	2.89	4.52	0.96
Green	3.56	2.77	4.14	0.86
Kishwaukee	3.91	3.06	3.70	0.73

Table 3. Average seasonal precipitation

Basin	Cold season (Oct-Mar)	Warm season (Apr-Sep)	Maximum recharge (Dec-Mar)	Minimum runoff (Jul-Aug)
	Precipitation (inches) for given season			
Big Muddy	18.58	22.69	12.29	6.88
Little Wabash	18.18	22.77	12.02	6.63
Skillet Fork	18.43	22.84	12.26	6.75
Embarras	16.21	22.53	10.39	6.76
Cache	22.53	24.54	15.50	6.84
Kaskaskia	15.63	22.63	9.98	6.74
Sangamon	14.20	22.28	8.76	6.65
Macoupin	14.46	23.21	9.01	7.18
Vermillion (North)	11.89	22.15	7.61	7.02
La Moine	12.80	23.36	7.76	7.36
Henderson Creek	12.80	22.56	8.00	7.01
Green	11.92	22.75	7.20	7.29
Spoon	12.19	22.38	7.33	6.81
Kishwaukee	12.17	21.96	7.32	7.24

Table 4. Basin groupings according to climatic index and average runoff/precipitation ratios

Basin	Annual BCI	Annual R/P	Oct-Mar	Seasonal Dec-Mar	R/P values Apr-Sept	Jul-Aug
Big Muddy	86	0.29	0.38	0.51	0.22	0.11
Little Wabash	87	0.27	0.33	0.44	0.21	0.12
Skillet Fork	87	0.27	0.34	0.46	0.21	0.09
Embarras	86	0.27	0.35	0.47	0.22	0.12
Kaskaskia	85	0.25	0.28	0.42	0.21	0.12
Cache	102	0.35	0.45	0.58	0.27	0.11
Macoupin	77	0.20	0.23	0.30	0.18	0.12
Sangamon	78	0.23	0.26	0.34	0.21	0.15
La Moine	76	0.22	0.26	0.34	0.19	0.13
Spoon	77	0.24	0.30	0.41	0.21	0.15
Henderson Creek	78	0.23	0.27	0.36	0.20	0.14
Green	76	0.23	0,30	0.38	0.18	0.12
Vermillion	77	0.24	0.26	0.39	0.23	0.12
Kishwaukee	81	0.22	0.32	0.42	0.17	0.10
Median	80	0.24	0.30	0.42	0.21	0.12

DEVELOPMENT AND TESTING OF BASIN EQUATIONS

The initial step in the water supply study involved development and testing of basin regression equations relating runoff to antecedent runoff and rainfall indices, mean temperature, and various precipitation parameters. For this purpose, use was made of all years of data for each season and sub-season.

Regression Equations

Tables 5 to 8 show the regression equations derived for each basin. The variables are shown in the order of their selection in reducing the standard error of the regression. Thus, for the Big Muddy in the cold season, the total seasonal precipitation was the most important variable, followed by September runoff, January precipitation, and fall (September-November) precipitation. From testing, the general equation selected to represent the basin runoff relation is:

$$R = a + bX_1 + cX_2 + dX_3 + eX^4$$

R is seasonal runoff; X_1 to X_4 are precipitation, temperature and antecedent runoff variables; and a, b, c, d, and e are the intercept and regression constants,

Regression Equation Variables

Evaluation was made of the relative importance of the various independent variables used in the stepwise correlation and regression analyses. In doing this, the four most important variables were determined for each basin and each season, and ranked according to their contribution in reducing the standard error of estimate in the basin regression equation. Table 9 summarizes this evaluation for the cold season, and shows the rank score and frequency of occurrence of each variable among the first four most important variables. The rank score was determined by allotting a score of 4, 3, 2, and 1, respectively, for ranks 1 through 4. The maximum possible rank score would be 56.

For the cold season, total seasonal precipitation ranked first among 11 of the 14 basins and had the highest rank score. The other most important variables, in general, were the antecedent index represented by September runoff, fall precipitation, and winter (December-February) precipitation. Total season precipitation showed an especially strong relationship in the four southernmost basins (Big Muddy, Skillet Fork, Little Wabash, and Cache) where simple correlation coefficients of 0.90 to 0.92 were obtained between R and $P_{Oct\text{-}Mar}$. All but the Cache lie in the claypan soil region.

Table 10 shows a similar tabulation for the warm season. The most important definitive variable was again total seasonal precipitation, but spring (March-May) precipitation replaced the antecedent index as the second most important factor. The sub-season, December-March, was similar to the total cold season in that total seasonal precipitation and antecedent index (November runoff) were the two strongest variables. The July-August period with its tendency for highly variable year-to-year precipitation and high evapotranspiration and infiltration rates had lower correlations than the other seasons and less dependence upon the sub-season total precipitation, which ranked third in importance behind July rainfall and June rainfall (antecedent index).

Multiple Correlation Coefficients

Table 11 shows the multiple correlations for each season in each of the 14 basins, based on the four most important variables. The correlation coefficients were relatively high in all seasons, but especially in the cold season period when replenishment of shallow groundwater aquifers maximizes, on the average, and when the percentage of precipitation converted to total runoff is greatest (see Table 4). Conversely, correlations are lowest in

Table 5. Cold season regression equations based on all years of data

Basin	Intercept	Variable 1*	Variable 2*	Variable 3*	Variable 4*
Big Muddy	-8.43	0.62 $P_{(\text{Oct-Mar})}$	2.98 R_{Sep}	0.44 P_{Jan}	0.23 $P_{(\text{Sep-Nov})}$
Little Wabash	-9.40	0.67 $P_{(\text{Oct-Mar})}$	11.98 R_{Sep}	0.39 P_{Jan}	0.29 P_{Nov}
Skillet Fork	-12.60	0.60 $P_{(\text{Oct-Mar})}$	0.47 $P_{(\text{Sep-Nov})}$	0.40 $P_{(\text{Dec-Feb})}$	--
Embarras	-7.79	0.38 $P_{(\text{Oct-Mar})}$	2.00 R_{Sep}	0.56 $P_{(\text{Dec-Feb})}$	0.32 $P_{(\text{Sep-Nov})}$
Cache	-5.69	1.07 $P_{(\text{Oct-Mar})}$	2.42 R_{Sep}	-2.42 N	--
Kaskaskia	-7.77	0.46 $P_{(\text{Oct-Mar})}$	2.81 R_{Sep}	0.36 $P_{(\text{Dec-Feb})}$	0.29 $P_{(\text{Sep-Nov})}$
Sangamon	-1.49	0.76 $P_{(\text{Oct-Mar})}$	4.21 R_{Sep}	-0.21 $T_{(\text{Dec-Feb})}$	0.34 P_{Dec}
Macoupin	-7.62	0.46 $P_{(\text{Oct-Mar})}$	2.48 R_{Sep}	0.30 $P_{(\text{Sep-Nov})}$	0.22 $P_{(\text{Dec-Feb})}$
Vermillion	-6.92	0.50 $P_{(\text{Oct-Mar})}$	3.62 R_{Sep}	0.10 N	0.13 $P_{(\text{Sep-Nov})}$
La Moine	-0.10	0.51 $P_{(\text{Oct-Mar})}$	0.27 P_{Sep}	-0.15 $T_{(\text{Dec-Feb})}$	0.49 R_{Sep}
Henderson Creek	-4.41	0.34 $P_{(\text{Sep-Nov})}$	0.14 N	0.58 P_{Feb}	0.80 R_{Sep}
Green	-4.32	0.32 $P_{(\text{Sep-Nov})}$	0.16 N	1.35 R_{Sep}	0.34 P_{Jan}
Spoon	-3.72	0.26 $P_{(\text{Sep-Nov})}$	0.23 $P_{(\text{Dec-Feb})}$	0.86 R_{Sep}	0.31 $P_{(\text{Oct-Mar})}$
Kishwaukee	-2.21	0.57 $P_{(\text{Oct-Mar})}$	3.26 R_{Sep}	0.18 P_{Sep}	-0.09 $T_{(\text{Dec-Feb})}$

* P - Precipitation (in.), R - Runoff (in.), S - Snowfall (in.), T - Seasonal temperature (°F),
N - Number of precipitation days, M - Maximum monthly precipitation,
Subscripts - Designate season or month.

Table 6. Warm season regression equations based on all years of data

Basin	Intercept	Variable 1*	Variable 2*	Variable 3*	Variable 4*
Big Muddy	12.25	0.04 $P_{(Apr-Sep)}$	0.46 $P_{(Mar-May)}$	0.78 M	-0.25 T
Little Wabash	-8.63	0.21 $P_{(Apr-Sep)}$	0.42 $P_{(Mar-May)}$	0.40 M	0.18 P_{Jun}
Skillet Fork	-7.96	0.40 $P_{(Mar-May)}$	0.83 M	0.32 P_{Apr}	0.23 P_{Jun}
Embarras	-8.37	0.19 $P_{(Apr-Sep)}$	0.38 $P_{(Mar-May)}$	0.44 P_{Jun}	0.45 M
Cache	31.73	0.21 $P_{(Apr-Sep)}$	0.35 $P_{(Mar-May)}$	0.56 M	-0.51 T
Kaskaskia	-7.79	0.12 $P_{(Apr-Sep)}$	0.43 $P_{(Mar-May)}$	0.43 P_{Jun}	0.47 M
Sangamon	-6.77	0.90 M	0.19 $P_{(Apr-Sep)}$	0.26 P_{Jun}	0.63 R_{Mar}
Macoupin	-10.16	0.54 $P_{(Mar-May)}$	0.16 $P_{(Apr-Sep)}$	0.36 P_{Jun}	0.42 M
Vermillion	-11.20	0.31 $P_{(Apr-Sep)}$	0.48 $P_{(Jun-Aug)}$	0.38 $P_{(Mar-May)}$	--
La Moine	13.83	0.21 $P_{(Apr-Sep)}$	0.29 $P_{(Mar-May)}$	0.52 M	-0.28 T
Henderson Creek	-7.46	0.33 $P_{(Apr-Sep)}$	0.41 P_{Jun}	0.21 $P_{(Mar-May)}$	0.54 R_{Mar}
Green	-6.12	0.26 $P_{(Apr-Sep)}$	1.09 R_{Mar}	0.43 P_{Apr}	0.41 P_{May}
Spoon	-8.48	0.39 $P_{(Apr-Sep)}$	0.25 $P_{(Mar-May)}$	0.75 R_{Mar}	0.26 P_{Jun}
Kishwaukee	-4.29	0.22 $P_{(Apr-Sep)}$	0.59 R_{Mar}	0.36 P_{Jun}	0.26 P_{May}

* P - Precipitation (in.), R - Runoff (in.), S - Snowfall (in.), T - Seasonal temperature (°F), N - Number of precipitation days, M - Maximum monthly precipitation, Subscripts - Designate season or month.

Table 7. Regression equations for December-March subseason based on all years of data

Basin	Intercept	Variable 1*	Variable 2*	Variable 3*	Variable 4*
Big Muddy	-4.75	0.60 $P_{(Dec-Mar)}$	1.40 R_{Nov}	0.54 P_{Jan}	0.37 P_{Dec}
Little Wabash	3.09	0.58 $P_{(Dec-Mar)}$	2.65 R_{Nov}	0.64 P_{Jan}	-0.23 T
Skillet Fork	-5.97	0.59 $P_{(Dec-Mar)}$	2.16 R_{Nov}	0.50 P_{Jan}	0.65 P_{Dec}
Embarras	-4.40	0.53 $P_{(Dec-Mar)}$	2.59 R_{Nov}	0.56 P_{Jan}	0.51 P_{Dec}
Cache	4.61	0.76 $P_{(Dec-Mar)}$	0.56 P_{Nov}	0.48 P_{Jan}	-0.32 T
Kaskaskia	-4.19	0.56 $P_{(Dec-Mar)}$	2.43 R_{Nov}	0.44 P_{Dec}	0.35 P_{Jan}
Sangamon	2.60	0.57 $P_{(Dec-Mar)}$	2.18 R_{Nov}	0.61 P_{Dec}	-0.23 T
Macoupin	-3.46	0.31 $P_{(Dec-Mar)}$	0.66 P_{Jan}	0.61 P_{Dec}	-0.05 S
Vermillion	-1.66	0.93 P_{Dec}	0.03 S	1.13 P_{Feb}	2.13 R_{Nov}
La Moine	1.53	0.45 $P_{(Dec-Mar)}$	1.65 R_{Nov}	-0.12 T	0.42 P_{Feb}
Henderson Creek	2.16	0.23 P_{Dec}	0.49 $P_{(Dec-Mar)}$	1.34 R_{Nov}	-0.15 T
Green	1.92	2.13 R_{Nov}	0.45 P_{Jan}	0.35 $P_{(Dec-Mar)}$	-0.13 T
Spoon	2.07	2.20 R_{Nov}	0.41 $P_{(Dec-Mar)}$	-0.12 $T_{(Dec-Feb)}$	0.31 P_{Jan}
Kishwaukee	-2.15	0.90 M	1.99 R_{Nov}	0.55 P_{Dec}	0.36 P_{Jan}

* P - Precipitation (in.), R - Runoff (in.), S - Snowfall (in.), T - Seasonal temperature (°F),
N - Number of precipitation days, M - Maximum monthly precipitation,
Subscripts - Designate season or month.

Table 8. Regression equations for July-August subseason based on all years of data

Basin	Intercept	Variable 1*	Variable 2*	Variable 3*	Variable 4*
Big Muddy	-2.49	0.42 $P_{(Jun-Aug)}$	0.24 P_{Jun}	-0.20 R_{Jun}	-0.10 N
Little Wabash	-4.46	0.37 P_{Jul}	0.12 P_{Jun}	0.18 P_{Aug}	0.04 T
Skillet Fork	-0.96	0.21 $P_{(Jun-Aug)}$	0.11 P_{Jul}	0.07 P_{Jun}	-0.11 N
Embarras	-1.79	0.17 P_{Jul}	0.23 R_{Jun}	0.19 $P_{(Jun-Aug)}$	0.13 P_{Jun}
Cache	-1.79	0.04 N	0.21 P_{Jul}	0.12 P_{Jun}	0.17 P
Kaskaskia	-1.44	0.35 P_{Jul}	0.13 P_{Jun}	0.10 P_{Aug}	0.20 R_{Jun}
Sangamon	-1.57	0.26 P_{Jun}	0.45 P_{Jul}	0.19 P_{Aug}	-0.18 N
Macoupin	-1.51	0.57 $P_{(Jun-Aug)}$	-0.43 N	0.13 P_{Jun}	-0.06 P_{Aug}
Vermillion	2.90	0.69 $P_{(Jun-Aug)}$	-0.58 N	0.25 R_{Jun}	-0.06 T
La Moine	-1.63	0.49 P_{Jul}	0.21 P_{Jun}	0.28 P_{Aug}	-0.25 N
Henderson Creek	-6.33	0.30 P_{Jul}	0.26 P_{Jun}	0.11 P_{Aug}	0.06 T
Green	-0.65	0.14 P_{Jul}	0.52 R_{Jun}	0.22 $P_{(Jun-Aug)}$	-0.21 N
Spoon	-1.31	0.29 $P_{(Jun-Aug)}$	0.23 P_{Jun}	0.19 P_{Jul}	-0.29 N
Kishwaukee	-0.45	0.08 P_{Jun}	0.23 $P_{(Jun-Aug)}$	-0.21 N	0.27 R_{Jun}

* P - Precipitation (in.), R - Runoff (in.), S - Snowfall (in.), T - Seasonal temperature (°F),
N - Number of precipitation days, M - Maximum monthly precipitation,
Subscripts - Designate season or month.

Table 9. Relative importance of independent variables in cold season, based on all years of data for 14 basins

Variable	Rank score	Frequency in ranks 1-4
$P_{Oct-Mar}$	44	11
R_{Sep}	33	13
P_{Sep}	5	2
$P_{Sep-Nov}$	21	9
$P_{Dec-Feb}$	11	6
N	10	4
$T_{Dec-Feb}$	6	4
P_{Oct}	0	0
P_{Nov}	2	1
P_{Dec}	1	1
P_{Jan}	5	3
P_{Feb}	2	1
P_{Mar}	1	1
S	0	0
M	0	0
Total	140	56

Table 10. Relative importance of independent variables in warm season, based on all years of data for 14 basins

Variable	Rank score	Frequency in ranks 1-4
$P_{Aug-Sep}$	50	13
R_{Mar}	10	5
$P_{Mar-May}$	33	11
$P_{Jun-Aug}$	3	1
M	18	9
N	0	0
$T_{Jun-Aug}$	3	3
P_{Mar}	1	1
P_{Apr}	4	2
P_{May}	2	2
P_{Jun}	16	9
P_{Jul}	0	0
P_{Aug}	0	0
P_{Sep}	0	0
Total	140	56

July-August when interception and evapotranspiration use a larger portion of the available rainfall. As shown by the R/P values in Table 4, 10-15% of the July-August rainfall is contributed to runoff, on the average, whereas 30-58% of the December-March precipitation is converted to runoff among the 14 basins.

Relative Importance of Equation Variables

Although four variables were used in most basin equations, one variable usually accounted for a major portion of the variance explained by the equation. Table 12 shows the total percentage of the variance explained by the cold and warm season equations and the percentage explained by the most important variable in each equation. The most important variable was the total season precipitation in most basins during both seasons (Tables 5-6).

Table 12 shows a median difference of 19% in both seasons between the total variance explained and that accounted for by the most important variable. Thus, equation results were very strongly dependent upon the major variable, even though the use of multiple meteorological and hydrological variables did considerably improve the accuracy of runoff estimates obtained with the basin equations.

Inter-Correlation of Variables

As indicated earlier, the variables used in the stepwise regression analyses to determine basin runoff are not strictly independent and, in some cases, pairs of variables could be highly correlated. The inter-correlation of variables was found to be most pronounced in the July-August equations. Therefore, tests were made to ascertain the importance of these inter-correlations in the basin regression equations. In these tests, all pairs of variables for which the simple correlation coefficient between any pair was 0.75 or greater were identified in the final 4-variable equation for each basin. Then, the variable which had the lesser weight in reducing the equation standard error was eliminated, and replaced by the top ranked variable remaining among those eliminated in obtaining the 4-variable equation. This would be the fifth ranked variable if only one pair of variables had a correlation coefficient $\geq$ 0.75 in a basin equation, but could be sixth or lower if more than one pair met the rejection criteria.

Results of the substitution process are summarized for the July-August equations in Table 13 for the nine basins affected. In general, the multiple correlation for the basin equation was lowered only slightly by the substitution process, but the changes were not considered to be of major importance in the first-approximation analyses being performed. Consequently, it was decided to use the original 4-variable equations for the hypothetical seeding analyses. In the warm season (April-September) and the cold season (October-March) only two basin equations had pairs of variables with correlations of 0.75 or greater, and no further evaluation of the effects on these basin regression equations was made.

Table 11. Multiple correlation coefficients for seasonal regression equations, based on all years of data

Basin	Area (Mi^2)	Oct-March	Dec-March	Apr-Sept	July-Aug
Little Wabash	3111	0.97	0.97	0.96	0.89
Big Muddy	785	0.94	0.94	0.93	0.82
Skillet Fork	464	0.95	0.95	0.95	0.80
Cache	243	0.95	0.93	0.92	0.83
Embarras	1513	0.95	0.94	0.94	0.81
Macoupin	875	0.92	0.86	0.95	0.83
Kaskaskia	1980	0.95	0.91	0.93	0.87
Sangamon	5120	0.93	0.94	0.93	0.85
Spoon	1600	0.89	0.87	0.88	0.85
La Moine	1310	0.94	0.90	0.92	0.85
Vermillion	568	0.91	0.91	0.96	0.87
Green	958	0.93	0.87	0.86	0.77
Henderson	428	0.91	0.85	0.89	0.86
Kishwaukee	1090	0.95	0.88	0.78	0.80
Range	243-5120	0.89-0.97	0.88-0.97	0.81-0.97	0.77-0.89
Medians	1027	0.94	0.91	0.94	0.84
Variance Explained (%)		88	83	88	71

Table 12. Variance explained in cold and warm season equations.

	Total variance explained (%)		Variance explained (%) by most important variable	
Basin	Cold	Warm	Cold	Warm
Big Muddy	88	86	85	61
Little Wabash	94	92	85	71
Skillet Fork	90	90	83	71
Cache	90	85	85	71
Embarras	90	88	72	66
Macoupin	85	90	66	67
Kaskaskia	90	86	71	59
Sangamon	86	86	66	75
Spoon	79	77	56	64
La Moine	88	85	58	74
Vermillion	83	92	54	79
Henderson Creek	83	79	64	64
Green	86	74	67	52
Kishwaukee	90	61	81	38
Median	88	86	69	67

Table 13. Multiple correlation coefficients before and after substituting for variable pairs with simple coefficients ≥0.75 in July-August regressions

Basin	Multiple correlation Before	After	Difference
Big Muddy	0.82	0.82	0.00
Skillet Fork	0.80	0.80	0.00
Cache	0.83	0.83	0.00
Macoupin	0.83	0.80	0.03
Kaskaskia	0.87	0.86	0.01
Vermillion	0.86	0.77	0.09
Spoon	0.84	0.82	0.02
Green	0.74	0.73	0.01
Kishwaukee	0.77	0.73	0.04

Average Output from Continuous Seeding Program

Past investigations, such as made by the National Academy of Sciences-National Research Council (MacDonald, 1966), have indicated average seeding-induced increases in precipitation of 10% to 20% under favorable conditions. Therefore, the equations in Tables 5-8 were used to calculate average runoff increases in each basin for each season and sub-season, assuming a capability to increase the major precipitation contributors to the seasonal runoff by an average of 20%. That is, a constant-change seeding model was assumed to operate continuously throughout the season under investigation. Results are summarized in Tables 14-15, which show average runoff increases in both inches and percent.

Tables 14 and 15 show that the median increase in natural runoff (no seeding) is approximately 2.3 times the precipitation increase in the October-March period (46% vs 20%), 1.6 times during December-March, 2.6 times in the total warm season, and 2.7 times in the July-August period. Examination of Tables 14 and 15 shows that the percentage increase in basin runoff is not dictated by basin size. The above results provide generalized estimates of potential enhancement under average year-to-year conditions. Obviously, seeding would be most beneficial in relative dry weather when water supplies are under stress. Conversely, suppression of runoff would be favored in normally wet periods. This subject will receive more detailed treatment later.

Table 14. Average runoff increases in cold season resulting from 20% seeding-induced precipitation increases, based on all years of data

Basin	October-March In.	October-March %	December-March In.	December-March %
Big Muddy	3.00	42	2.04	33
Little Wabash	2.83	47	1.74	33
Skillet Fork	3.77	60	2.14	38
Cache	3.04	30	3.18	35
Embarras	2.61	46	1.63	33
Macoupin	2.11	63	1.06	39
Kaskaskia	2.44	50	1.49	36
Sangamon	2.13	58	1.26	43
Spoon	1.41	38	0.71	24
La Moine	1.52	46	0.81	30
Vermillion	1.94	62	0.70	24
Henderson Creek	1.54	44	0.88	30
Green	1.50	42	0.67	24
Kishwaukee	1.49	38	0.87	28
Median	2.12	46	1.16	33

Table 15. Average runoff increases in warm season resulting from 20% seeding-induced precipitation increases, based on all years of data

Basin	April-September In.	April-September %	July-August In.	July-August %
Big Muddy	2.39	48	0.68	87
Little Wabash	2.70	55	0.48	61
Skillet Fork	2.56	53	0.31	50
Cache	2.85	43	0.51	65
Embarras	2.66	54	0.47	61
Macoupin	2.87	69	0.47	55
Kaskaskia	2.51	53	0.41	51
Sangamon	2.19	46	0.51	53
Spoon	2.48	53	0.46	46
La Moine	2.29	51	0.52	53
Vermillion	3.25	65	0.46	55
Henderson Creek	2.29	51	0.54	56
Green	1.82	44	0.22	24
Kishwaukee	1.44	39	0.20	27
Median	2.49	52	0.47	54

CONSTRAINTS ON SEEDING TO INCREASE STREAMFLOW

Before proceeding further with our analyses of potential runoff enhancement from seeding-induced precipitation, it is appropriate to consider constraints to seeding operations. No specific investigation was made of the magnitude of the constraints that might be placed upon cloud seeding undertaken to augment runoff for water supply augmentation in Illinois. Limitations in funds and personnel, along with anticipated limited application of weather modification for this purpose in Illinois (discussed later), led to the decision to by-pass such a study. Rather, available information in the literature has been used to provide a first approximation of the magnitude of constraints.

Operational constraints could result from several causes. These include conditions when high streamflow poses a potential flood threat, insufficient storage capacity in reservoirs, interference with planting and harvesting, forecasts of severe weather (heavy rainfall, hail or tornadoes) in the potential seeding region, plentiful soil moisture from previous precipitation, failure to recognize favorable weather conditions for seeding (forecasting failures), and maintenance problems with seeding aircraft.

Smith (1970) in a study of operational constraints in Kansas estimated that only about 50% of the potential increase in runoff from cloud seeding could be utilized, on the average, for augmentation of water supplies. Lumb and Linsley (1971) in a study of an eastern Kansas watershed concluded that under favorable conditions only about 50% of the runoff, or less than 25% of the added precipitation, could be stored for use. As a first approximation, the 50% operational constraint found in the Kansas studies can be applied to Illinois and the Midwest.

This reduction applied to the runoff increases in Tables 14-15 provides a more realistic estimate of the average seeding-induced increases to be expected from a continuous year-to-year seeding operation. Seasons with below-normal precipitation, especially cold seasons, would be expected to have much smaller constraints, and these would be limited primarily to failures in recognizing potential seeding conditions and equipment failures that might abort seeding operations. Therefore, a 10%-20% constraint would appear more logical in the really dry periods. However, this small constraint would still further reduce the seeding-augmented runoff which would normally be small in these periods (discussed later), and, therefore, reduce the probability of seeding-induced precipitation significantly alleviating water-supply shortages under these conditions.

EFFECT OF SEEDING PROGRAM ON RUNOFF ENHANCEMENT IN NEAR-NORMAL TO BELOW-NORMAL SEASONS

Particular attention was given to evaluation of potential increases in runoff through weather modification during seasons of near-normal to below-normal runoff. These are periods during which augmentation of water supplies through weather modification could be beneficial in the Midwest. Conceivably, increased precipitation in near-normal years could be used to increase the storage in impounding reservoirs operating below full capacity. During below-normal years when abnormal drawdown might be occurring in many reservoirs, alleviation of the drawdown rate could lessen the probability of critical shortages if the precipitation deficiency became prolonged. In communities obtaining water supplies directly from streams, increasing the base flow in below-normal years could lessen the probability of critical shortages if the drought condition continued.

In developing the regression equations for this phase of the water supply study, the lower two-thirds of the runoffs for the period of record on each basin were used. It was concluded that use of two-thirds of the years would provide a sample of sufficient size to use as a first approximation of seeding effects with the stepwise regression technique. Elimination of the upper one-third of the seasonal runoffs removes excessive weighting of the regressions by the heavy runoffs which are not applicable to this analysis. Use of data only for those conditions under which weather modification is perceived to occur should provide a more reliable empirical relation for estimating potential benefits.

The estimates of potential augmentation of runoff in near-normal to below-normal seasons assume that seeding operations will be carried on throughout such periods. In practice, this would be difficult to achieve because of forecasting limitations. The most likely time for all-season seeding would be when a moderate to severe drought is in progress at the start of the season, so that reservoir drawdown is sufficient to warrant operations. However, with dry conditions prevailing, seeding effectiveness in augmenting runoff would be below average because of soil moisture requirements. Without dry conditions prevailing at the start of either the cold or warm season, seeding would await the initiation of such conditions and sufficient reservoir drawdown to stimulate action. Then, soil moisture deficiencies, along with excessive evaporation during the warm season, would reduce the average effectiveness of seeding. That is, the runoff augmentation would likely be less than induced under normal or average weather and soil conditions. The average augmentations in the preceding section, based on a continuous year-to-year seeding program, provide a measure of the expected seeding effectiveness under average conditions.

The results presented in this section assume an all-season seeding program. Therefore, results should be interpreted as first approximations of the average runoff to be expected in near-normal to below-normal seasons under favorable conditions with no operational constraints. If one reduces the calculated augmentations by 50%, as suggested in the discussion of constraints in the previous section, a conservative estimate of probable augmentation is obtained. In any case, results provide only an estimate of the average augmentation for seeding programs carried out during all near-normal to below-normal seasons to increase water storage.

The averages would not apply to seeding carried out only in below-normal seasons, which is a subject discussed in the next section. As stated before, a seeding program carried out during near-normal to below-normal seasons to increase reservoir storage would be a logical undertaking in many areas of the country where dependence is wholly or largely upon surface supplies. In fact, if the capability to routinely produce runoff augmentation in near-normal to slightly below-normal seasons could be established with a high degree of reliability, this supplementary source of supply could then be integrated into reservoir design, and would lead not only to a more stable source of supply but could reduce size requirements of reservoirs, and, hence provide a substantial economic benefit.

Regression Equations

Tables 16-19 show the basin regression equations, based upon use of data for those seasons with near-normal to below-normal runoff. In each equation, the variables are shown in the order of their selection in reducing the standard error of estimate. In several cases,* the original limitation of four variables was allowed to increase to five because of a substantial decrease in standard error with this single addition. In the July-August period, only three were used in some basins, since the fourth had no significant effect on the standard error.

In most basins, the cold season regressions show the total seasonal precipitation to be the most important variable. Overall, the antecedent runoff index (September runoff) ranked second in importance. Similarly, for the cold sub-season (December-March), the total seasonal and antecedent index were the most important variables, in general. The rating of variables in relative importance was more variable in the warm season and July-August periods. In the warm season, spring precipitation occurred most often; in the July-August period, the antecedent rainfall (June) was most important overall.

Precipitation-Runoff Relations in Cold Season

Average precipitation-runoff relations for the cold season, based on the data for near-normal to below-normal seasons, are summarized in Table 20, grouped by region of the state. Elimination of the upper one-third of the runoff data resulted in a decrease of only 0.04-0.09 in the correlation coefficients compared with all storms combined (Table 11) for the October-March period. With the near-normal to below-normal runoff data, 71% to 88% of the

Table 16. Cold season regression equations based on near-normal to below-normal seasons

Basin	Intercept	Variable 1*	Variable 2*	Variable 3*	Variable 4*
Big Muddy	-7.68	0.60 $P_{(Oct-Mar)}$	7.12 $R_{(Sep)}$	0.36 $P_{(Nov)}$	0.05 S
Little Wabash	-5.24	0.39 $P_{(Oct-Mar)}$	0.08 S	5.21 $R_{(Sep)}$	0.11 $P_{(Sep-Nov)}$
Skillet Fork	-8.14	0.57 $P_{(Oct-Mar)}$	0.09 S	3.91 $R_{(Sep)}$	0.37 $P_{(Jan)}$
Embarras	-6.75	0.37 $P_{(Oct-Mar)}$	3.15 $R_{(Sep)}$	0.32 $P_{(Sep-Nov)}$	0.35 $P_{(Dec-Feb)}$
Cache	-6.52	0.78 $P_{(Oct-Mar)}$	4.76 $R_{(Sep)}$	0.08 S	0.12 N
Kaskaskia	-5.40	0.35 $P_{(Oct-Mar)}$	3.01 $R_{(Sep)}$	0.22 $P_{(Sep-Nov)}$	0.27 $P_{(Dec-Feb)}$
Sangamon	-4.30	0.66 $P_{(Nov)}$	0.17 $P_{(Sep)}$	0.32 $P_{(Oct-Mar)}$	2.67 $R_{(Sep)}$
Macoupin	-2.65	0.55 $P_{(Sep)}$	0.10 $P_{(Oct-Mar)}$	0.28 $P_{(Nov)}$	0.16 $P_{(Mar)}$
Vermillion (North)	-4.04	0.36 $P_{(Oct-Mar)}$	20.33 $R_{(Sep)}$	0.04 N	0.17 $P_{(Nov)}$
La Moine	-0.45	0.38 $P_{(Oct-Mar)}$	0.34 $P_{(Sep)}$	-0.11 T	0.48 $P_{(Feb)}$
Henderson Creek	-3.09	0.31 $P_{(Sep-Nov)}$	0.47 $P_{(Feb)}$	0.09 N	0.74 $R_{(Sep)}$
Green	0.18	0.38 $P_{(Oct-Mar)}$	3.86 $R_{(Sep)}$	-0.12 T	0.28 $P_{(Feb)}$
Spoon	1.44	0.26 $P_{(Dec-Feb)}$	0.23 $P_{(Sep-Nov)}$	0.80 $P_{(Feb)}$	-0.11 T
Kishwaukee	-0.93	0.42 $P_{(Oct-Mar)}$	11.87 $R_{(Sep)}$	-0.17 T	0.27 $P_{(Dec-Feb)}$

* P - Precipitation (in.), R - Runoff (in.), S - Snowfall (in.), T - Temperature (°F),
N - Number of precipitation days, M - Maximum monthly precipitation,
Subscripts - Designate season or month.

Table 17. Warm season regression equations based on near-normal to below-normal seasons

Basin	Intercept	Variable 1*	Variable 2*	Variable 3*	Variable 4*
Big Muddy	14.52	0.11 $P_{(Mar-May)}$	-0.20 T	0.38 $P_{(Apr)}$	0.43 $P_{(May)}$
Little Wabash	-4.63	0.46 M	0.25 $P_{(Mar-May)}$	0.44 $P_{(May)}$	0.18 $P_{(Jun)}$
Skillet Fork	-4.72	0.35 $P_{(Mar-May)}$	0.39 M	0.23 $P_{(Jun)}$	0.23 $P_{(Apr)}$
Embarras	9.56	0.17 N	0.33 $P_{(Mar-May)}$	0.33 $P_{(Jun)}$	-0.18 T
Cache	8.59	0.20 $P_{(Apr-Sep)}$	0.31 $P_{(May)}$	0.36 $P_{(Apr)}$	-0.15 T
Kaskaskia	19.98	-0.29 T	0.38 M	0.23 $P_{(Mar-May)}$	0.18 $P_{(Jun)}$
Sangamon	13.88	0.22 $P_{(Apr-Sep)}$	0.75 $R_{(Mar)}$	0.37 $P_{(Jun)}$	-0.23 T
Macoupin	-1.99	0.76 M	0.47 $P_{(May)}$	0.17 N	0.43 $R_{(Mar)}$
Vermillion (North)	-4.60	0.21 $P_{(Apr-Sep)}$	0.42 $P_{(Jun)}$	0.61 $R_{(Mar)}$	0.18 $P_{(Mar-May)}$
La Moine	-2.72	0.31 $P_{(Mar-May)}$	0.10 $P_{(Jun-Aug)}$	0.54 $R_{(Mar)}$	0.27 $P_{(Jun)}$
Henderson Creek	12.10	0.19 $P_{(Jun)}$	0.07 N	-0.16 T	0.17 $P_{(May)}$
Green	-3.80	1.21 $R_{(Mar)}$	0.32 N	0.13 $P_{(Jun)}$	0.11 $P_{(Apr)}$
Spoon	14.26	0.12 $P_{(Apr-Sep)}$	0.19 $P_{(Mar-May)}$	-0.21 T	0.17 $P_{(Jun)}$
Kishwaukee	6.37	0.33 $P_{(May)}$	0.28 $P_{(Jun)}$	-0.08 T	0.08 $P_{(Jul)}$

* P - Precipitation (in.), R - Runoff (in.), S - Snowfall (in.), T - Temperature (°F),
N - Number of precipitation days, M - Maximum monthly precipitation,
Subscripts - Designate season or month.

Table 18. December-March regression equations based on near-normal to below-normal seasons

Basin	Intercept	Variable 1*	Variable 2*	Variable 3*	Variable 4*	Variable 5*
Big Muddy	3.62	0.54 $P_{(Dec-Mar)}$	1.83 $R_{(Nov)}$	-0.20 T	0.30 $P_{(Dec)}$	
Little Wabash	1.48	3.56 $R_{(Nov)}$	0.47 $P_{(Dec-Mar)}$	-0.14 T	0.22 $P_{(Dec)}$	
Skillet Fork	-5.26	0.57 $P_{(Dec-Mar)}$	3.74 $R_{(Nov)}$	0.06 S	0.32 $P_{(Dec)}$	
Embarras	0.80	2.57 $R_{(Nov)}$	0.45 $P_{(Dec-Mar)}$	0.54 $P_{(Dec)}$	-0.13 T	
Cache	-2.13	0.80 $P_{(Dec-Mar)}$	0.91 $R_{(Nov)}$	0.04 S	-0.09 T	
Kaskaskia	-1.94	1.63 $R_{(Nov)}$	0.30 $P_{(Dec-Mar)}$	0.43 $P_{(Dec)}$	0.20 $P_{(Nov)}$	
Sangamon	1.32	0.55 $P_{(Dec)}$	1.80 $R_{(Nov)}$	0.24 $P_{(Dec-Mar)}$	-0.10 T	
Macoupin	1.50	0.51 $R_{(Nov)}$	0.22 M	0.01 S	0.23 $P_{(Feb)}$	-0.06 T
Vermillion (North)	4.81	0.42 $P_{(Dec-Mar)}$	3.41 $R_{(Nov)}$	-0.19 T	-0.06 S	
La Moine	1.00	0.21 $P_{(Dec-Mar)}$	2.12 $R_{(Nov)}$	0.71 $P_{(Feb)}$	-0.09 T	0.28 $P_{(Dec)}$
Henderson Creek	2.63	0.23 $P_{(Dec-Mar)}$	1.67 $R_{(Nov)}$	-0.13 T	0.32 $P_{(Jan)}$	0.22 $P_{(Feb)}$
Green	1.29	0.57 $P_{(Jan)}$	0.33 M	2.60 $R_{(Nov)}$	0.65 $P_{(Feb)}$	-0.11 T
Spoon	1.79	2.05 $R_{(Nov)}$	0.30 $P_{(Dec-Mar)}$	-0.10 T	0.40 $P_{(Feb)}$	
Kishwaukee	-1.52	0.66 $P_{(Jan)}$	2.06 $R_{(Nov)}$	0.48 M	0.52 $P_{(Feb)}$	

* P - Precipitation (in.), R - Runoff (in.), S - Snowfall (in.), T - Temperature (°F),
N - Number of precipitation days, M - Maximum monthly precipitation,
Subscripts - Designate season or month.

Table 19. July-August regression equations based on near-normal to below-normal seasons

Basin	Intercept	Variable 1*	Variable 2*	Variable 3*	Variable 4*
Big Muddy	-0.17	0.04 $P_{(Jun)}$	0.03 $P_{(Jul-Aug)}$	0.02 $R_{(Jun)}$	0.01 $P_{(Jul)}$
Little Wabash	-1.51	0.10 $P_{(Jul-Aug)}$	0.04 $P_{(Jun)}$	0.01 T	
Skillet Fork	0.27	0.08 $P_{(Jul)}$	0.03 $R_{(Jun)}$	0.02 $P_{(Jun)}$	-0.01 T
Embarras	-0.26	0.27 $R_{(Jun)}$	0.05 $P_{(Jul)}$	0.03 $P_{(Jul-Aug)}$	0.03 $P_{(Jun)}$
Cache	0.87	0.07 N	0.12 $R_{(Jun)}$	-0.01 T	
Kaskaskia	-0.19	0.14 $P_{(Jul)}$	0.15 $R_{(Jun)}$	0.04 $P_{(Jul-Aug)}$	-0.04 N
Sangamon	1.28	0.31 $R_{(Jun)}$	0.10 $P_{(Jul)}$	-0.02 T	
Macoupin	1.16	0.09 $P_{(Jul)}$	0.03 $P_{(Jun)}$	-0.02 T	0.02 $P_{(Jul-Aug)}$
Vermillion (North)	-0.19	0.06 $P_{(Jun)}$	0.06 $P_{(Jul)}$	0.07 $R_{(Jun)}$	
La Moine	-1.07	0.08 $P_{(Jul-Aug)}$	0.22 $R_{(Jun)}$	0.02 $P_{(Aug)}$	0.01 T
Henderson Creek	1.73	-0.03 T	0.07 $P_{(Jul-Aug)}$	0.07 $P_{(Jun)}$	
Green	-0.78	0.34 $R_{(Jun)}$	0.05 $P_{(Jul)}$	0.02 $P_{(Jul-Aug)}$	0.01 T
Spoon	-0.05	0.17 $R_{(Jun)}$	0.08 $P_{(Jul)}$	0.04 N	
Kishwaukee	-0.67	0.23 $R_{(Jun)}$	0.03 $P_{(Jul-Aug)}$	0.03 $P_{(Jun)}$	0.01 T

* P - Precipitation (in.), R - Runoff (in.), S - Snowfall (in.)., T - Temperature (°F),
N - Number of precipitation days, M - Maximum monthly precipitation,
Subscripts - Designate season or month.

variance is explained among the 14 basin equations, compared with 79% to 94% with regressions derived from all years combined.

R/P values show that, on the average, 6% to 12% less of the natural precipitation is converted to runoff in the near-normal to below-normal cold seasons than for all seasons combined. Also, as shown by the R/P values, a greater proportion of the natural precipitation is converted to runoff in the Cache Basin in the Shawnee Hills and in the Big Muddy and Embarras basins with their predominance of claypan soils.

As indicated earlier, the two most important variables in the regressions were total seasonal precipitation and September runoff, the same as found with all years combined. Rank scores were 45 and 27, respectively, for the above variables for which the maximum possible score is 56.

The trends noted above for the October-March period are also present in relations for the sub-season, December-March, in Table 21. Comparison with Table 11 shows the median correlation coefficient for the 14 basins lowering from 0.91 to 0.84 between all years combined and years with near-normal to below-normal runoff. However, the correlation of 0.84 still indicates a relatively strong relationship and an acceptable method of evaluating seeding-induced runoff potential. A substantial decrease occurs in R/P which lowers from a median of 0.42 for all years (Table 4) to 0.29 in the near-normal to below-normal years. This represents a median decrease of 13% in the average percentage of precipitation converted to runoff.

The next analytical step involved use of the basin equations for the near-normal to below-normal seasons to calculate the average runoff enhancement for an assumed seeding-induced increase of 20% in each of the major precipitation contributors to basin runoff in the equations. Estimates for a given basin were obtained by substituting actual weather data for each year of record, but increasing the precipitation factors by 20%. Results are summarized in Table 22 which shows average runoff enhancement in inches and in percent of naturally-occurring runoff, similar to Tables 14-15.

Comparison of Table 22 with Table 14 shows the median runoff increase changing from 2.12 inches to 1.18 inches, a decrease of 44%. These statistics provide a measure of the difference in seeding-induced runoff for water supply replenishment that would occur between a continuous year-to-year seeding program and one undertaken only in those years with near- to below-normal runoff. Of course, constraints would likely be greater, on the average, in a continuous seeding program, so that the average difference might be somewhat lower than indicated by the above statistics and the -individual basin values provided in Tables 14 and 22.

Comparison of seeding-induced runoff in Table 14 and 22 for the four experimental basins where a seeding program would most likely be useful for water supply purposes in Illinois provides information of the seeding potential. Averages of runoff augmentation for the Big Muddy, Little Wabash,

Table 20. Average rainfall-runoff relations in cold season, based on near-normal to below-normal runoff periods

Basin	Runoff (inches)	Precipitation (inches)	R/P	Multiple correlation coefficient
		South-Southwest		
Big Muddy	4.44	16.13	0.28	0.87
Little Wabash	3.60	16.14	0.22	0.94
Skillet Fork	3.57	16.33	0.22	0.88
Cache	6.32	19.11	0.33	0.92.
Macoupin	1.61	12.88	0.13	0.91
		Central		
Embarras	3.66	14.60	0.25	0.91
Kaskaskia	2.99	13.88	0.22	0.86
Sangamon	2.11	12.85	0.16	0.87
Vermillion	1.82	11.19	0.16	0.92
		West-Northwest-North		
Spoon	2.33	11.05.	0.21	0.88
La Moine	2.22	11.77	0.19	0.88
Green	2.29	10.92	0.21	0.84
Henderson Creek	2.29	11.61	0.20	0.85
Kishwaukee	2.54	11.03	0.23	0.92
Range	1.61-4.44	10.92-19.11	0.13-0.33	0.84-0.94
Median	2.31	12.87	0.22	0.88

Table 21. Average rainfall-runoff relations in December-March, based on near-normal to below-normal runoff periods

Basin	Runoff (inches)	Precipitation (inches)	R/P	Multiple correlation coefficient
		South-Southwest		
Big Muddy	3.94	10.47	0.38	0.84
Little Wabash	3.14	10.18	0.31	0.94
Skillet Fork	3.28	10.79	0.30	0.91
Cache	5.60	12.79	0.44	0.84
Macoupin	1.24	8.01	0.15	0.72
		Central		
Embarras	3.04	9.13	0.33	0.88
Kaskaskia	2.60	8.67	0.30	0.80
Sangamon	1.62	7.85	0.21	0.85
Vermillion	1.78	7.10	0.25	0.80
		West-Northwest-North		
Spoon	1.93	6.63	0.29	0.84
La Moine	1.78	6.89	0.27	0.83
Green	1.92	6.85	0.28	0.81
Henderson Creek	1.98	7.56	0.26	0.74
Kishwaukee	2.09	7.23	0.27	0.90
Range	1.24-3.94	6.63-12.79	0.15-0.44	0.72-0.94
Median	2.03	7.93	0.29	0.84

Skillet Fork, and Enibarras during the cold season are 3.05 inches for a continuous year-to-year program and 2.05 inches for a program restricted to near-normal to below-normal seasons. NOW, assuming a 50% operational constraint in both cases, the averages are reduced to 1.5 3 inches and 1.03 inches, respectively. However, these represent 24% and 17%, respectively, of the average seasonal runoff, based on long-term records. Thus, the potential runoff augmentation from seeding operations is substantial, not only for a continuous year-to-year seeding program, but for a more logical undertaking that restricts seeding to near-normal to below-normal seasons. The primary question then concerns whether this potential increase is needed in Illinois in those areas depending to a large extent upon surface supplies. This question will be discussed in a later section.

Comparison of statistics for the sub-season, December-March, leads to conclusions similar to those discussed above for the entire cold season. Thus, for the four basins analyzed above, calculations show that with a 50% operational constraint, the average runoff augmentation is 24% and 20%, respectively, of the long-term mean for seeding programs based on continuous year-to-year operations and those restricted to near-normal to below-normal years.

Table 23 shows low flow frequency relations during the cold season for the 14 basins. The 25-year recurrence interval provides a measure of the runoff to be expected in severe drought conditions , whereas the 2-year value represents median or near-normal runoff. Comparison of these-two runoff columns points out clearly the problem in achieving substantial runoff increases through seeding in very dry periods. The 10-year recurrence portrays typical runoffs in a moderate drought. However, in most basins, the 10-year runoff is still only a small fraction of normal (as measured by the 2-year value). For example, in the first four basins in Table 23, the 10-year runoff averages only 20% of the 2-year value. Furthermore, these basins are located in the region in which moderate to severe droughts occur with above-average frequency, and where surface waters are a major source of water supply. Runoff augmentations from seeding programs of the magnitude obtained for average conditions in near-normal to below-normal years (Table 22) could not be expected with the soil moisture deficiencies existing in moderate to severe drought periods.

Precipitation-Runoff Relations in Warm Season

Table 24 shows average runoff, precipitation, runoff/rainfall ratios, and multiple correlation coefficients for the 14 basin regressions in the warm season. Elimination of one-third of the data sample resulted in a substantial decrease in correlation coefficients for the warm season. However, except for three basins in the northwest and northern parts of the states, the correlations remained relatively high, exceeding 0.80 which represents a decrease of 0.05-0.13 from the correlations for all storms combined (Table 11). Tables 4 and 24 show that the R/P values decreased 0.07, on the average, or a reduction of approximately 7% in the amount of

Table 22. Average runoff increases in cold season resulting from 20% seeding-induced increases in precipitation based on near-normal to below-normal years of runoff

Basin	October-March In.	October-March %	December-March In.	December-March %
Big Muddy	2.26	51	1.31	34
Little Wabash	1.68	46	1.07	34
Skillet Fork	2.26	63	1.56	47
Cache	2.41	38	2.14	38
Embarras	2.00	55	1.06	35
Macoupin	0.85	53	0.28	33
Kaskaskia	1.61	54	0.80	31
Sangamon	1.20	57	0.58	36
Spoon	0.76	32	0.49	25
La Moine	1.20	54	0.57	32
Vermillion (North)	0.86	47	0.37	21
Henderson Creek	1.04	45	0.53	27
Green	0.91	40	0.54	28
Kishwaukee	1.16	46	0.60	29
Median	1.18	49	0.59	32

Table 23. Low flow frequency relations for cold season

Basin	Runoff (inches) for given recurrence interval (years) 2	5	10	25
Big Muddy	6.55	2.65	1.14	0.20
Little Wabash	4.95	2.55	1.40	0.10
Skillet Fork	5.20	2.00	0.94	0.16
Embarras	5.50	2.00	0.92	0.28
Cache	8.55	4.30	2.77	1.53
Kaskaskia	4.47	1.47	0.66	0.22
Sangamon	3.00	1.13	0.63	0.32
Macoupin	2.80	0.85	0.33	0.07
Vermillion (North)	2.75	0.93	0.38	0.13
La Moine	3.15	1.31	0.74	0.38
Spoon	3.25	1.52	1.01	0.63
Henderson Creek	3.05	1.37	0.90	0.70
Green	3.05	1.70	1.21	0.84
Kishwaukee	3.75	1.45	1.14	0.95

precipitation converted to runoff in the near-normal to below-normal warm seasons. Note the close similarity in the R/P values for most basins in Table 24, which indicates similarity in reaction to warm season precipitation. Except for Cache and Macoupin, all R/P values were in the 0.14-0.17 range under the conditions analyzed.

The most important variables in the basin equations were spring rainfall, June rainfall, and summer mean temperature. March-May precipitation was among the four variables used in 11 basins , whereas June rainfall and summer temperature appeared in 8 of the stepwise regressions. Rank scores were 24, 22, and 16, respectively, for the three parameters, based upon scores of 4, 3, 2, and 1 for ranks 1, 2, 3, and 4 among the variables. Thus, when the upper one-third of the runoffs are eliminated, the seasonal runoff is controlled to the greatest extent by spring rainfall rather than total seasonal rainfall. Furthermore, June rainfall (start of summer) and summer mean temperature become increasingly important. This is especially pronounced in the case of summer temperature which moved from a rank score of only 3 for all seasons combined to 16 for near-normal to below-normal seasons.

Correlations for the July-August period were considerably lower than for the entire warm season, although the 14-basin median of 0.76 is still quite high (Table 25). However, the very low percentage of rainfall converted to runoff with near-normal to below-normal rainfall (median of 6%) indicates that weather modification performed to increase municipal water supplies during July-August would probably not be economically rewarding in Illinois.

Table 26 shows average runoff increases in the warm season resulting from a seeding-induced increase of 20% in the precipitation parameters that are primarily responsible for the runoff. Comparison of Table 26 with Table 15 shows a large decrease in the seeding-induced runoff when seeding is restricted to near-normal seasons. Thus, the 14-basin median reduces from 2.49 inches for all seasons combined to 1.01 inches when seeding is limited to the drier seasons. This is a considerably greater change than found for the cold season, and is due primarily to the much greater evapotranspiration in the warm season. Furthermore, evapotranspiration will increase with temperature, and dry periods usually have above-normal temperatures in the warm season.

The same calculations were performed for Big Muddy, Skillet Fork, Little Wabash, and Embarras as discussed previously for the cold season. Assuming a 50% operation constraint, calculations indicate that in a continuous year-to-year seeding program in the April-September period an average of 1.29 inches of runoff augmentation would be obtained, or 26% of the normal runoff based on long-term averages. This corresponds closely with the 24% increase obtained for the cold season. Similarly, when the 50% constraint was applied to the results for near-normal to below-normal years, runoff augmentation of 0.60 inch was obtained, which corresponds to only 12% of the long-term runoff for the warm season, and considerably below the cold season estimates of 1.03 inches and 17%. Greater evapotranspiration requirements in the warm season are believed to be primarily responsible for the cold and warm season differences in seeding effectiveness to increase runoff.

Table 24. Average rainfall-runoff relations in warm season, based on near-normal to below-normal runoff periods

Basin	Runoff (inches)	Precipitation (inches)	R/P	Multiple correlation coefficient
		South-Southwest		
Big Muddy	2.92	20.27	0.14	0.84
Little Wabash	3.12	20.12	0.16	0.86
Skillet Fork	2.83	20.60	0.14	0.89
Cache	3.86	21.59	0.18	0.82
Macoupin	2.36	21.00	0.11	0.83
		Central		
Embarras	3.23	20.44	0.16	0.87
Kaskaskia	3.12	20.73	0.15	0.87
Sangamon	3.43	20.65	0.17	0.8.8
Vermillion	3.42	19.96	0.17	0.94
		West-Northwest-North		
Spoon	3.03	20.33	0.15	0.75
La Moine	2.80	21.00	0.13	0.84
Green	2.96	21.02	0.14	0.84
Henderson Creek	2.86	20.14	0.14	0.63
Kishwaukee	2.80	20.46	0.14	0.70
Range	2.80-3.86	19.96-21.59	0.11-0.18	0.63-0.94
Median	3.00	20.60	0.14	0.84

Table 25. Average rainfall-runoff relations in July-August, based on near-normal to below-normal runoff periods

Basin	Runoff (inches)	Precipitation (inches)	R/P	Multiple correlation coefficient
		South-Southwest		
Big Muddy	0.18	5.69	0.03	0.75
Little Wabash	0.32	5.84	0.05	0.70
Skillet Fork	0.21	5.70	0.04	0.68
Cache	0.27	5.83	0.05	0.75
Macoupin	0.28	6.25	0.04	0.74
		Central		
Embarras	0.37	6.00	0.06	0.77
Kaskaskia	0.38	6.18	0.06	0.88
Sangamon	0.56	6.39	0.09	0.83
Vermillion	0.29	5.21	6.06	0.64
		West-Northwest-North		
Spoon	0.48	5.86	0.08	0.77
La Moine	0.46	6.43	0.07	0.71
Green	0.54	6.80	0.08	0.83
Henderson Creek	0.46	5.90	0.08	0.77
Kishwaukee	0.47	6.68	0.07	0.78
Range	0.18-0.56	5.21-6.80	0.03-0.08	0.64-0.88
Median	0.37	5.95	0.06	0.76

Table 26. Average runoff increases in warm season resulting from 20% seeding-induced increases in precipitation, based on near-normal to below-normal years of runoff

Basin	April-September In.	April-September %	July-August In.	July-August %
Big Muddy	0.80	27	0.07	39
Little Wabash	1.55	50	0.15	48
Skillet Fork	1.51	53	0.06	18
Cache	1.40	36	0.06	22
Embarras	0.91	28	0.09	24
Macoupin	1.26	53	0.10	36
Kaskaskia	1.01	32	0.12	32
Sangamon	1.17	34	0.06	11
Spoon	0.94	31	0.05	8
La Moine	1.01	36	0.11	24
Vermillion (North)	1.46	43	0.08	28
Henderson Creek	0.26	9	0.14	33
Green	0.18	6	0.07	11
Kishwaukee	0.49	18	0.07	15
Median	1.01	33	0.08	26

Table 26 shows that a 20% increase in precipitation during July-August produces only a small increase in runoff. Thus, the median increase is only 0.08 inch with a range from 0.05 to 0.15 inch among the 14 basins. Such increases would provide little help in alleviating water supply shortages.

Table 27 shows low flow frequency relations for the warm season on the 14 basins. Interpretation and use is the same as discussed in conjunction with Table 23.

General Conclusions

The general conclusion from analyses of data for near-normal to below-normal seasons is that substantial increases in runoff for augmentation of surface water supplies could be achieved, provided that an average seeding-induced increase of 20% in the pertinent precipitation parameters could be achieved and assuming that a seeding program is carried out continuously during such seasons. The opportunity for increasing surface runoff in such situations appears to be somewhat better in the cold season when soil moisture demands and evapotranspiration are less than in the warmer part of the year. However, when droughts of the order of 10-year to 25-year recurrences prevail, frequency distributions of seasonal low flow and consideration of both meteorological and hydrological factors do not suggest major returns from a seeding program. More on this subject will be presented in the next section.

Table 27. Low flow frequency relations for warm season

Basin	Runoff (inches) for given recurrence interval (years)			
	2	5	10	25
Big Muddy	4.20	1.88	1.15	0.58
Little Wabash	4.02	2.30	1.70	0.84
Skillet Fork	3.80	1.67	1.04	0.61
Embarras	4.35	2.35	1.53	0.83
Cache	5.30	2.37	1.52	0.93
Kaskaskia	4.25	2.35	1.44	0.68
Sangamon	4.75	2.50	1.63	0.99
Macoupin	3.05	1.45	0.98	0.28
Vermillion (North)	4.35	2.60	1.88	1.00
La Moine	3.85	1.75	1.12	0.62
Spoon	4.10	2.23	1.52	0.92
Henderson Creek	3.95	2.04	1.42	0.93
Green	3.85	2.27	1.65	1.05
Kishwaukee	3.38	2.33	1.92	1.55

POTENTIAL RUNOFF ENHANCEMENT IN BELOW-NORMAL SEASONS

Seasonal runoff for the five basins with the longest continuous records was divided into thirds. These included seasons in which the runoff was above normal (upper 1/3), near normal (middle 1/3), and below normal (lower 1/3). Basins used were the Big Muddy, Embarras, Kaskaskia, La Moine, and Spoon which have continuous records of 48 to 55 years. Regression analyses were then performed to obtain separate equations for each group for comparison with the equations based upon use of all runoff data. Separation of data for the other basins into thirds was not attempted because the' resulting samples were considered too small to develop empirical equations of sufficient reliability for evaluation of potential seeding effects. Primary interest in the above stratifications was in the lower third of the seasonal runoffs.

Warm Season Runoff

In most cases, the multiple correlation coefficients for the equations developed from the warm season stratifications were reduced substantially from those obtained with all warm season data. Thus, in the below-normal regression equation, the Big Muddy correlation coefficient was 0.81 compared with 0.93 with the overall seasonal equation, or a decrease in variance explained from 86% to 66%. Changes of similar magnitude were obtained with the other basins, except for the La Moine where the multiple correlation coefficient in the below-normal and overall equations were nearly equal.

Comparisons of average R/P values for the below-normal seasons were made with those for all seasons combined and for the July-August period when streamflow is normally low. Average R/P in the below-normal warm seasons (April-September) was nearly the same as the average ratio for all seasons combined in the July-August period (Table 4) in the Big Muddy, Embarras, and Kaskaskia basins in the southern and central parts of the state. Thus, it was concluded that rainfall-runoff conditions in the July-August period for all years combined would reflect conditions during warm seasons with dry conditions in the south central and southern parts of the state where any future weather modification experiment would be undertaken. Analyses indicated that the warm season regressions for below-normal years were unreliable because of the great natural variability in warm season rainfall and runoff from year-to-year and the relatively small sample upon which it was necessary to base the basin equations.

Average values of seasonal runoff (R), rainfall (P), and R/P are shown in Table 28 for the lower 1/3 of the warm season runoffs. Also shown are the multiple correlation coefficients for the regression equations for the five basins. Average seasonal values of R/P and multiple correlations were provided earlier in Table 11 and 15.

In the below-normal equations, spring rainfall was the most important variable; March-May rainfall ranked first in two basins, and May rainfall was first in the other three basins. This agrees well with the warm season equations based upon all years of data in which March-May rainfall ranked first in importance in all five basins.

Cold Season Runoff

Cold season records for the five basins with longest continuous records were divided into three groups, similar to the method followed in the warm season stratifications. Primary emphasis was placed on the third of the seasons with lowest runoff, since these would be periods when weather modification to increase water supplies from surface sources and shallow aquifers would be most helpful. Regression equations developed from these low runoff data provided stronger relationships than obtained with similar warm season data, since precipitation and evapotranspiration tend to be less variable in the cold season. The most important variables in the below-normal seasons were total seasonal precipitation and September runoff (antecedent index). These are the same highest ranked variables as found with all cold seasons combined.

Table 29 shows a comparison of average runoff, precipitation, runoff/precipitation ratios, and multiple correlation coefficients for the lower one third of the seasonal runoffs in the five basins. Multiple correlation coefficients and runoff/precipitation ratios for the regression based upon use of all years of data are shown also for comparison purposes. Table 30 shows a comparison of average seeding-induced increases in runoff between all cold seasons and those seasons with the lowest one-third of the runoffs.

Table 28. Average runoff, precipitation, runoff/rainfall ratios, and multiple correlation coefficients for below-normal runoff in warm seasons

Basin	R (in.)	P (in.)	R/P	Multiple correlation coefficient
Big Muddy	1.74	17.62	0.10	0.81
Embarras	2.04	17.72	0.12	0.86
Kaskaskia	1.82	17.90	0.10	0.64
La Moine	1.61	18.77	0.09	0.94
Spoon	1.97	17.73	0.11	0.76

Table 29. Comparison of average cold-season runoff-precipitation relations between below-normal years and all years combined

	Below-normal years				All years	
Basin	Average runoff (in.)	Average precipitation (in.)	R/P	r*	R/P	r*
Big Muddy	2.07	13.43	0.15	0.85	0.38	0.94
Embarras	1.60	12.71	0.13	0.92	0.35	0.95
Kaskaskia	1.33	12.44	0.11	0.92	0.28	0.95
La Moine	1.05	10.63	0.10	0.89	0.26	0.94
Spoon	1.32	10.41	0.13	0.85	0.30	0.89
Median	1.33	12.44	0.13	0.89	0.30	0.94

* Multiple correlation coefficient

Table 30. Comparison of average runoff augmentation during cold season between all years combined, near-normal to below-normal years, and below-normal years, assuming 20% seeding-induced increase in precipitation

	Runoff increase (in.) for given type season			Runoff ratio*	
Basin	All years	Near- to below-normal	Below-normal	Near- to below-normal	Below-normal
Big Muddy	3.00	2.26	1.17	0.75	0.39
Embarras	2.61	2.00	0.62	0.77	0.24
Kaskaskia	2.44	1.61	0.58	0.66	0.24
La Moine	1.52	1.20	0.54	0.80	0.36
Spoon	1.41	0.76	0.53	0.54	0.38
Median	2.44	1.61	0.58	0.75	0.36

* Ratio of runoff augmentation in below-normal and near-normal to below-normal seasons to runoff augmentation for all seasons combined

Table 29 shows some decrease in the strength of the runoff-rainfall relations when only the below-normal runoff seasons are used. However, a relatively high degree of correlation still persists with the smaller sample of dry-period data. The percentage of the seasonal precipitation converted to runoff decreases from averages of 26% to 38% when all years are combined to 10% to 15% in the dry seasons. When the 20% seeding-induced increase in precipitation is applied to the two sets of equations (Table 30), there is a large decrease in the actual runoff increase between the two groups of seasons.

The difficulty in producing substantial increases in runoff to alleviate surface water-supply deficiencies in dry periods is clearly illustrated in Tables 29 and 30. Thus, the R/P values in Table 29 show that only 10% to 15% of the natural precipitation is converted to runoff, on the average, in below-normal cold seasons. The average for all years combined ranges from 26% to 38%, with a median that is over twice that for the below-normal years. This major decrease in percentage of precipitation converted to runoff is then emphasized further in the statistics of Table 30. This table shows that the average increase in runoff from an assumed 20% increase in precipitation from seeding in a dry year ranges from 24% to 39% (runoff ratio) among the five basins compared with the average for all years combined. Other calculations (not shown) indicated that the precipitation would have to be increased by more than 50% in the below-normal years to approach the average for all years shown in Table 30.

General Conclusions

The average runoff augmentations for below-normal years provide guidance in estimating seeding potential in the drier periods. However, these averages do not reflect the really severe drought conditions, such as the type that occurs once in 25 years on the average, since the statistics are averages for the lowest 33% of the years on record. Thus the averages of Table 30 are more representative of runoff augmentation to be expected approximately once in 15 years. In general, it would appear that increases in the severe drought years, at least, would be insufficient to produce much alleviation of water supply shortages, unless the natural precipitation could be increased by very large amounts through weather modification (of the order of 100% or greater) in extremely dry periods.

ANNUAL LOW FLOW CHARACTERISTICS IN ILLINOIS

Emphasis in this report has been upon potential for seasonal runoff augmentation, as outlined in the Project Work Plan. The seasonal approach was adopted in view of previous findings by Hudson and Roberts (1955) with regard to the optimum period for replenishment of surface and shallow ground water aquifers in central and southern Illinois. However, it is also desirable to examine prospects for augmentation on an annual basis. For this purpose, we have depended upon the results from previous Water Survey studies relating to annual relations for low flow.

Stall (1964) made an extensive study of low flows in Illinois streams to provide information for impounding reservoir design. Table 31 was abstracted from material presented in his report to provide a measure of the severity of runoff reduction in drought periods and further perspective with regard to the weather modification potential in alleviating water supply deficiencies. In Table 31, low flow (runoff) frequency relations have been shown for 12-month durations and selected recurrence intervals for each of the 14 basins used in our study. The low flow has been expressed as a percentage of the mean annual discharge for each of the three selected recurrence intervals.

The greatest reduction in low flow for a severe 12-month drought occurs in southern and south-central Illinois, and includes the major surface water supply region of the claypan soils region of southern Illinois (Figs. 1., 3). Thus, the 25-year recurrence shows runoff varying from 5% to 7% of the normal annual discharge in this region, but this increases to over 20% in the northern part of the state (Green River, Kishwaukee) where drought severity is generally less than in the southern part of the state.

Table 31. Frequency relations for annual low flow in 14 study basins

Basin	Mean Annual discharge (inches)	Low flow for given recurrence (years) in percent of mean discharge		
		5	10	25
Big Muddy*	12.1	39	12	5
Little Wabash*	10.9	42	19	7
Skillet Fork*	11.1	36	11	5
Embarras*	10.6	44	25	7
Cache	16.7	36	20	13
Kaskaskia	9.7	40	24	6
Macoupin	7.5	29	15	4
Sangamon	8.4	46	31	15
Vermillion	8.1	45	24	14
La Moine	7.8	49	19	10
Spoon	8.4	49	26	17
Henderson Creek	8.0	48	29	20
Green	7.7	62	33	22
Kishwaukee	7.6	53	36	24

* Claypan soils - major surface water supply region.

A study of low flow-precipitation relations for Illinois (Huff and Changnon, 1964) shows that in a 25-year drought only about 3% of the precipitation in the 12 consecutive months of minimum precipitation is converted to runoff in the claypan soil region of Fig. 3. This percentage increases to 5% in the Green River basin of northern Illinois. In a relatively moderate drought of 5-year recurrence, the Huff-Changnon study indicates approximately 13% of the 12-month precipitation converted to runoff in the claypan region. In an average year, the conversion amounts to approximately 27% of the annual precipitation. The above statistics again emphasize the problem in substantially increasing the streamflow from surface runoff in severe drought periods, whether viewed on a seasonal or annual basis.

COMPARISON OF MEAN ANNUAL RUNOFF COMPUTED BY ILLINOIS AND KANSAS METHODS

Smith (1970) in a study of water utilization aspects of weather modification in Kansas employed a method of determining annual rainfall-runoff relationships through use of basin mean rainfall and the basin climatic index, BCI, developed by Thornthwaite (19 31). In so doing, he followed a method suggested by Guisti and Lopez (1967) in which they indicated the annual ratio of runoff to precipitation (R/P) is an empirical function of BCI, which is related to average monthly precipitation and temperature by:

$$BCI = 115 \sum_{1}^{12} (P/T-10)^{1.11}$$

Smith developed curves relating (1) annual precipitation to BCI utilizing the above equation, and (2) BCI to R/P. Employing these two sets of curves, he developed a third set relating percent increase in mean runoff to R/P, assuming uniform increases in precipitation of 5, 10, and 20% from weather modification. The reader is referred to the Smith report for further details.

It was decided that it would be useful to compare the seeding-induced increases in annual runoff calculated from the Kansas BCI-R/P relationship with the results obtained from the stepwise regression analyses used in the Illinois study. Results of the comparison are illustrated in Table 32, based upon hypothetical seeding-induced precipitation increases of 10% and 20% in the natural precipitation. The calculations were made for the 14 basins being used in the Illinois study which have been grouped into geographic locations (S-SW, Central, W-NW-N) for which medians have been determined in Table 32. Seeding-induced changes have been expressed as the percentage increase in runoff for 10% and 20% seeding-induced increases in precipitation on each basin. Results are based upon a continuous year-to-year seeding program.

In general, the Kansas method yields somewhat higher seeding-induced. gains in annual runoff. In the basins of central Illinois, relatively close agreement was reached between the two methods in 3 of 4 basins with both 10% and 20% precipitation increases. The largest differences were obtained with the southern basins. Combining all basins, close agreement . was obtained between the state medians.

Considering the various sources of sampling error in the computations and the known variation of BCI with topography, the two methods of computation are in fair agreement, especially with the 10% precipitation increases. Both show substantial increases in runoff from seeding-induced increases of 10% to 20% in precipitation.

MINIMUM RUNOFF IN ILLINOIS DROUGHTS

In the Kansas study (Smith, 1970), it was pointed out that many of their streams were running dry during drought periods, so that seeding for increasing water supplies would have little or no effect. That is, 10% to

Table 32. Comparison of seeding-induced increases in mean annual runoff calculated by Kansas and Illinois methods, based on 10% and 20% seeding-induced increases in mean annual precipitation

	Seeding-induced runoff increase (%)			
	10% Precipitation increase		20% Precipitation increase	
Basin	Kansas	Illinois.	Kansas	Illinois
		South-Southwest		
Big Muddy	24	22	56	45
Little Wabash	35	26	66	51
Skillet Fork	35	29	65	57
Cache	30	19	59	37
Macoupin	57	33	95	66
Median	35	26	66	51
		Central		
Embarras	26	25	56	50
Kaskaskia	37	26	60	52
Sangamon	26	26	58	52
Vermillion	20	31	40	63
Median	26	26	57	52
		West-Northwest-North		
Spoon	18	22	44	45
La Moine	30	25	69	49
Green	17	22	54	43
Henderson Creek	26	23	63	48
Kishwaukee	26	19	59	39
Median	26	22	59	45
State Median	26	25	59	50

20% rainfall increases would be mostly if not completely used by infiltration and evapotranspiration before reaching the streams as runoff.

Monthly runoff data for the 14 experimental basins used in the Illinois study were scanned to determine the minimum monthly runoff on record for the 14 basins. Results showed that the minimum was zero or near zero for all basins in southern ' Illinois and most of the other areas, as shown in Table 33. The severe drought of 1953-54 produced the minimum most frequently, and the 1940 drought ranked second in the number of record low monthly runoffs.

Next, the 1953-54 drought which was especially severe in south and south central Illinois was examined to determine minimum runoff for periods of 1, 2, and 3 months. Results are summarized in Table 34. For the three consecutive months of minimum streamflow (September-November 1953) the total runoff was less than 0.01 inch in the most southern basins (Big Muddy, Little Wabash, Skillet Fork, and Cache) and only 0.02 to 0.04 inch in the central and south central basins (Macoupin, Kaskaskia, and Sangamon).

Except for Cache, the total cold season runoff (October-March) in the. 1953-54 period was less than 0.10 inch in the southern and central basins. Mean runoff for the cold season ranges from 3.34 inches for Macoupin to 10.13 inches for Cache. Thus-, under very severe drought conditions (average recurrence intervals of 25 years or longer), such as experienced in 1953-54, seeding-induced precipitation would have little or no effect on increasing water supplies from surface water and shallow groundwater aquifers unless large rainfall increase's could be generated.

Table 33. Minimum monthly runoff recorded on experimental basins

Basin	Runoff (in.)	Month and Year
Big Muddy	0.000	9/40, 9/53, 10/38, 10/40
Little Wabash	0.001, 0.002	9/53, 10/53, 10/64
Skillet Fork	0.000	8/40, 9/40, 10/40, 9/53, 11/53
Cache	0.000, 0.001	8/36, 10/63, 10/53
Macoupin	0.001, 0.003	1/56, 9/53
Embarras	0.006, 0.009	9/54, 8/54
Kaskaskia	0.009, 0.011, 0.013	10/53, 9/54, 9/64
Sangamon	0.042, 0.044	9/40, 9/54
La Moine	0.006, 0.010	10/56, 11/56, 10/63
Spoon	0.021, 0.024, 0.030, 0.031	9/63, 9/40, 10/63, 11/40
Green	0.054, 0.057, 0.059	9/40, 9/53, 10/53

Table 34. Minimum runoff (inches), 1- to 3-month periods, 1953-54 drought

	1-Month		2-Month		3-Month		Oct.-Mar.	
Basin	R	Date	R	Date	R	Date	R	Year
Big Muddy	0.000	9/53	0.004	9-10/53	0.008	9-11/53	0.05	53-54
Little Wabash	0.001	9/53	0.003	9-10/53	0.006	9-11/53	0.06	53-54
Skillet Fork	0.000	9/53, 11/53	0.002	9-10/53	0.002	9-11/53	0.02	53-54
Cache	0.001	10/53	0.003	9-10/53	0.006	9-11/53	1.22	53-54
Macoupin	0.003	9/53	0.010	9-10/53	0.018	9-11/53	0.05	53-54
Embarras	0.006	9/54	0.031	9-10/53	0.043	9-11/53	0.08	53-54
Kaskaskia	0.009	10/53, 11/53	0.018	10-11/53	0.031	9-11/53	0.09	53-54
Sangamon	0.044	9/53, 11/53	0.104	9-10/53	0.148	9-11/53	0.37	53-54
La Moine	0.011	11/53	0.026	11-12/53	0.058	10-12/53	0.54	53-54
Spoon	0.021	9/53	0.075	9-10/53	0.113	9-11/53	1.36	53-54
Green	0.057	9/53	0.116	9-10/53	0.186	9-11/53	0.79	53-54

Further reference to studies of the 1953-54 drought (Illinois Water Survey, 1958) showed that runoff during the 12-month period of lowest streamflow (August 1953-July 1954) ranged from 0.2 inch to 1 inch in the most severe drought areas. The 24-month minima (January 1953-December 1954) ranged from less than 2 to 5 inches in the most severely affected areas.

POTENTIAL EROSION AND SEDIMENTATION EFFECTS FROM SEEDING-INDUCED RAINFALL AND RUNOFF IN ILLINOIS

A limited study was undertaken regarding the potential effects of weather modification in Illinois on soil erosion and stream sedimentation. A literature review on the subject has been accomplished, and discussions held with informed personnel in the Water Survey Hydrology Section on the Illinois situation. Certain information obtained is summarized below.

With regard to calculating changes in erosion and sedimentation load with increasing rainfall, use of the Universal Soil Loss Equation (shown below) has been recommended. This equation has had widespread use and has been employed in a previous Illinois study of erosion loads in the drainage basin of Crab Orchard Lake in the southern part of the state (Stall, et al., 1954)

$$E = KLSCPR \text{ , where} \tag{1}$$

E - average annual soil loss; K - soil erodibility factor; L,S - topographic factors (gradient, slope); C - crop management factor; P - conservation practice factor; and R - factor expressing erosion potential of average annual precipitation.

R is given by the following equation (Wischmeier and Smith, 1958)

$$R = \Sigma \; EI \text{ , where} \tag{2}$$

E - kinetic energy of storm rainfall, and I - 30-minute maximum rain intensity.

Thus; Equations (1) and (2) show erosion directly proportional to the rainfall factor, which, in turn, is related to the summation of the product of the kinetic energy of rainfall and maximum 30-minute rainfall intensities in each storm. If seeding resulted in no change in the intensity distribution characteristics of storms, erosion would then be directly proportional to the ratio of seeded to non-seeded total rainfall. That is, a 20% increase in annual rainfall would cause a 20% increase in total erosion in tons/acre/year.

Stream sedimentation in tons/acre will be less than the soil erosion since part of the eroded soil will not reach the stream. However, as a first approximation, it has been recommended that we assume any percentage increase in erosion will result in approximately the same percentage increase in sedimentation. That is, if the soil erosion is 5 tons/acre/year and sedimentation is 3 tons/acre/year, a 20% increase in soil erosion from additional rainfall (such as seeding-induced) will cause a 20% increase in stream sedimentation.

At this time, however, we have been unable to obtain an acceptable method for placing dollar values on increased erosion and sedimentation that could result from weather modification in Illinois. A study was recently initiated at the University of Illinois under Dr. Earl Swanson (our consultant on the previous Bureau of Reclamation contract, 14-06-D-6843) to study economic damages from stream sedimentation resulting from soil erosion. However, this study has not progressed to the stage where results and conclusions are available. One method for obtaining a first approximation of increased sedimentation disbenefit at a given location would be to calculate how much it would shorten the reservoir life, and calculate the increased cost of the reservoir in dollars/year resulting from the shorter life. Normalizing dollar values would be a problem here.

The regions in which surface water supply is important are the Galesburg Plain in western Illinois, the Springfield Plain in the west central part of the state, and the claypan soils of southern Illinois (Fig. 3).

According to Water Survey studies, median erosion is 2.2 tons/acre/year in the Galesburg Plain compared with 1.3 in the Springfield Plain, and 1.5 in the claypan soils. However, the erosion variability is much greater in the Springfield and Galesburg Plains than in the claypan soils. Therefore, considering all pertinent regions, erosion is a lesser problem in southern Illinois (proposed location of any future weather modification experiment) than elsewhere. Sedimentation measurements in Illinois streams made by the Water Survey support the above observed erosion characteristics. The erosion difference is due to the "tighter" soils, on the average, in the southern part of the state. Soil erosion, and, consequently, stream sedimentation can be controlled to a large extent by conservation practices. For example, Stall (1962) has shown from a study of 9 Illinois, reservoir watersheds that deposition in these reservoirs could be reduced by 43% to 92% through proper watershed conservation.

As indicated earlier, any increased soil erosion and associated stream sedimentation resulting from weather modification would be proportional to induced changes in the rainfall intensity regime of a given watershed, other factors being equal. At this time, it is not possible to define reliably . from available knowledge whether significant alteration of the rainfall intensity regime would result from precipitation enhancement; that is, we do not know whether cloud seeding would tend to increase the volume of precipitation through intensification of the natural rainfall rates, increase in duration of natural rainfall, or a combination of both enhancement factors. Atmospheric scientists are not in agreement on the seeding effect. Opinions range from major increases in natural rainfall rates to significant decreases in rates accompanied by substantial increases in rainfall duration.

In view of the lack of existing knowledge regarding seeding effects on the natural rainfall intensity characteristics, it was concluded that this phase of the study should be terminated. A meaningful evaluation of the erosion-sedimentation problem can not be made without definition of the seeding-induced intensity effect. As a first approximation, it is recommended that erosion and sedimentation be considered to vary directly with the amount of seeding-induced precipitation; this assumes that the seeding will not significantly affect the intensity distribution characteristics of the natural rainfall regime. Watershed conservation practices are probably considerably more important in controlling erosion and sedimentation than alterations (adverse or beneficial) that would be induced from weather modification programs.

BENEFITS FROM POTENTIAL WATER SUPPLY AUGMENTATION IN ILLINOIS

Only limited success was achieved in evaluation of the economic aspects of water supply benefits through precipitation augmentation in Illinois. A graduate student in economics at the University of Illinois was employed part-time during summer 1972 to assist on this phase of the work. His contribution was largely a review of the literature pertaining to application of economics in weather modification. Results provided little assistance for the Illinois evaluation. Most available information is largely qualitative or inappropriate for evaluation of the Illinois situation.

Assistance was obtained in assessing the potential benefits of water supply augmentation in Illinois from several members of the Hydrology Section, Illinois State Water Survey, and included those engineers most familiar with the surface water and shallow groundwater hydrology of the State. Results of the assessment are summarized below.

Surface Water Augmentation

Consultation with surface water engineers indicated that there is no source of information on the number and frequency of reservoirs that experience problems in dry periods in Illinois. The practice of designating an emergency varies greatly with the community - some will initiate emergency measures when the reservoir capacity has lowered a third, whereas others will do nothing until the storage is nearly exhausted.

Stall (1965) published results of an Illinois study regarding the relation between impounding reservoir net yield and pumpage in dry periods. Based upon data from 41 reservoirs in central and south central Illinois, he found that, in general, Illinois reservoirs can withstand a 40-year drought (low flow) before completely emptying. Subsequent additional analyses lowered the low flow frequency to a 25-year drought condition. Although there was considerable scatter about the mean derived by Stall, it was most frequently on the high side; that is, some communities have reservoirs capable of operating throughout a 50-year drought or longer. A few communities would have problems in a drought of 15-year or 20-year frequency. However, through initiation of emergency measures pumpage could probably be reduced by 1/4 with no significant hardships and to 1/2 before the problem becomes severe in these cases. Thus, by emergency measures initiated early, a 25-year design might survive a 35-year drought, and a 15-20 year design could function in a 20-25 year drought.

Conceivably, seeding-induced rainfall could be helpful to those municipalities that take their water supply directly from rivers through use of low-head, run-of-the-river impoundments. These are used mostly by small communities and there are approximately 40 such installations in Illinois along the various rivers. Additional rainfall in near-normal periods might help by increasing the base flow.

There is also a possibility that seeding-induced rainfall which only causes a minor rise in a major river, such as the Mississippi, could be useful. This basin storage would provide additional water for use along rivers where large amounts are withdrawn. However, it is nearly impossible to place a dollar value on this type of use, since the water would be used incrementally along the river, and there would be losses to interception, depression storage, etc. Many factors would enter into an economic evaluation of the added water.

Shallow Groundwater Aquifers

There is a possible advantage in seeding to increase the water supply in shallow sand and gravel aquifers in areas where they are used extensively, since utilization of the added water takes place in months compared with years in deep aquifers. It is unlikely that any benefits would accrue during summer, but the possibility of an economic gain is present in the late fall to early spring when recharge of groundwater normally occurs. It is estimated that any seeding-induced increase in rainfall during the warmer one-half of the year would result in a negligible amount of infiltration into the water table. Some possible economic benefits to shallow aquifers due to seeding-induced precipitation include the following:

1) Reduced pumping lifts would be required if the water table is sufficiently increased.
2) Wells could perhaps be spaced closer together which would reduce transmission costs.
3) Higher yields per well may reduce the number of wells necessary to meet requirements.
4) Higher yields from shallow aquifers might lessen the need for alternative sources which may be more expensive.
5) An increase in precipitation at critical times would reduce the amount of ground water used for irrigation.

However, most of the above potential benefits can only be evaluated qualitatively, and it is estimated by the groundwater engineers that the economic benefits would not be appreciable.

Conclusions

The general conclusion reached from our investigation is that 1) informed hydrologists believe weather modification would not provide a major benefit to water supply in Illinois, unless it could provide substantial additions in relatively severe drought periods, such as experienced in the early 1950's in Illinois, 2) the frequency with which weather modification would be useful is not readily available from existing information on water supply shortages in the past, 3) an economic evaluation of potential benefits is nearly impossible to make with any high degree of reliability, and 4) agriculture would probably be the primary beneficiary of cloud seeding in Illinois.

Thus, the results of our investigation indicated that major benefits to water supplies in Illinois would result only if precipitation modification could provide alleviation of shortages in relatively severe drought conditions. Therefore, it was decided to proceed with a study aimed toward an evaluation of the potentialities of precipitation modification in severe droughts. This study, which was not part of the original work plan, is summarized in the Second Technical Report under Contract 14–06-D-7197.

SUMMARY AND CONCLUSIONS

Data and Analytical Methods

Research was carried out to provide quantitative estimates of the potential effects of cloud seeding in augmenting surface water supplies in Illinois, a typical midwestern state. Basically, Illinois data from 14 basins with a minimum of 30 years of continuous records were used to provide a measure of potential water-supply benefits under various basin characteristics. Particular emphasis was placed upon the southern and south central parts of the state where surface waters are a primary source of water supply. Because of existing soils, climate, and geomorphic conditions, seeding-induced precipitation would be most beneficial in the southern one-third of the state from both water supply and agricultural considerations. As part of this study, investigation was made of the frequency of serious water shortages in Illinois with major emphasis on impounding reservoirs. Limited consideration was given also to potential erosion and sedimentation problems associated with weather modification.

Stepwise correlation and regression techniques were used to derive basin equations which related seasonal runoff to antecedent indices, precipitation parameters, and temperature conditions. The year was divided into two basin seasons, the cold season from October through March, and the warm season from April through September. Two sub-seasons were also investigated. These included the December-March period when shallow-aquifer replenishment is most favored, and the July-August period when evapotranspiration losses are normally greatest.

Hypothetical seeding was applied with each basin equation to obtain estimates of runoff augmentation from seeding-induced precipitation increases of 20%. The seeding was assumed to increase the major precipitation parameters in each basin equation by 20%. Actual weather conditions and antecedent runoff conditions for each year of basin record were used to determine the hypothetical seeding effects from the basin equation.

Potential Seeding-induced Increases in Runoff

The hypothetical seeding effects were evaluated under three sets of conditions. First, equations were developed from all years of record and the hypothetical seeding applied. This was done primarily for evaluating and testing the applicability of the analytical technique.

After applicability of the analysis method was established satisfactorily utilizing the entire data sample, a more logical approach to the potential-effects of cloud seeding on basin runoff was' undertaken. It was assumed that precipitation augmentation would most likely be restricted to those periods when the streamflow was near-normal to below-normal. Conceivably, under near-normal conditions reservoir storage could be increased through seeding to provide protection against the possibility of drought at a later time, and in below-normal conditions the need for alleviation of reservoir drawdown would be a distinct possibility. Results indicated that the potential exists for substantial increase in streamflow through precipitation augmentation in near-normal to slightly below-normal periods of runoff, except during the July-August period of excessive evapotranspiration.

Next, five basins with continuous records ranging from 48 to 55 years were used to. develop basin equation based only upon below-normal runoff periods. Records were not considered adequate on the other basins to perform this restricted analysis. However, precipitation augmentation would be most useful for alleviation of water-supply deficiencies during such periods. Relationships developed for the warm season were considered too unstable for estimating seeding-induced increases from seeding operations. The sample was apparently too small in view of the large year-to-year natural variability in rainfall and runoff in the warm season. However, it was found that the relationships developed for July-August, the maximum evapotranspiration period, for all years of data combined could serve as a useful guide in estimating warm season benefits from seeding during below-normal runoff periods. The cold season relationships for below-normal seasons were found to be more stable and are considered acceptable for estimating seeding-induced runoff increases.

Results for the cold seasons of below-normal runoff clearly illustrated the difficulty in producing substantial increases in runoff to alleviate surface water-supply deficiencies in dry periods. Calculations indicated that precipitation would have to be increased by over 50%, on the average, in below-normal years to achieve the runoff augmentation obtained with a 20% increase in precipitation in a year with near-normal runoff. The warm season seeding effectiveness would need to be even greater, since it was found that only 10% of the rainfall, on the average, is converted to runoff in warm seasons with below-normal runoff.

When consideration is given to operational constraints, the best available information indicates that no more than 50% of the potential seeding-induced runoff could be utilized, on the average, in near-normal periods in the Midwest. In below-normal periods during the cold season, this constraint might be lowered to approximately 10%-20%. However, this relatively small loss would further deplete the small output of seeding-induced runoff indicated from our calculations for Illinois.

Table 35 shows a condensed comparison of the average seeding-induced increases in runoff during the cold and warm seasons, based upon an assumed 20% increase in the natural precipitation from seeding activities and no constraints on seeding operations. This comparison is shown for the five basins with longest continuous records among the 14 basins investigated. Reference to the cold season tabulations shows R/P decreasing from a median value of 0.30 for all years of record combined (climatic average) to 0.22

Table 35. Comparison of average seeding-induced increases in runoff during cold and warm seasons from 20% increase in precipitation

Cold season comparisons

Basin	All years combined: No-seed runoff (inches)	R/P	Seeding increase in.	%	Near to below-normal years: No-seed runoff (inches)	R/P	Seeding increase in.	%	Below-normal years: No-seed runoff (inches)	R/P	Seeding increase in.	%
Big Muddy	7.05	0.38	3.00	42	4.44	0.28	2.26	51	2.07	0.15	1.17	57
Embarras	5.69	0.35	2.61	46	3.66	0.25	2.00	55	1.60	0.13	0.62	38
Kaskaskia	4.92	0.28	2.44	50	2.99	0.22	1.61	54	1.33	0.11	0.58	44
La Moine	3.31	0.26	1.52	46	2.22	0.19	1.20	54	1.05	0.10	0.54	52
Spoon	3.68	0.30	1.41	38	2.33	0.21	0.76	32	1.32	0.13	0.53	40
Median	4.92	0.30	2.44	46	2.99	0.22	1.61	54	1.33	0.13	0.58	44

Warm season comparisons

Basin	All years combined: No-seed runoff (inches)	R/P	Seeding increase in.	%	Near to below-normal years: No-seed runoff (inches)	R/P	Seeding increase in.	%	Below-normal years: No-seed runoff (inches)	R/P	Seeding increase in.	%
Big Muddy	5.00	0.22	2.39	48	2.92	0.14	0.80	27	1.74	0.10	--	--
Embarras	4.93	0.22	2.66	54	3.23	0.16	0.91	28	2.04	0.12	--	--
Kaskaskia	4.76	0.21	2.51	53	3.12	0.15	1.01	32	1.82	0.10	--	--
La Moine	4.51	0.19	2.29	51	2.80	0.15	1.01	36	1.61	0.09	--	--
Spoon	4.68	0.21	2.48	53	3.03	0.13	0.94	31	1.97	0.11	--	--
Median	4.76	0.21	2.48	53	3.03	0.15	0.94	31	1.82	0.10	--	--

for near-normal to below-normal years, and to 0.13 for below-normal years. The percentage of precipitation converted to runoff in dry seasons (below-normal) is less than 50% of the average seasonal value. The seeding-induced runoff under these conditions shows the below-normal seasons having only about 25% of that achieved by the 20% precipitation increase in an average season (0.58/2.44). The reduction in precipitation converted to runoff (R/P) is even greater for three south central and southern basins (Big Muddy, Embarras, and Kaskaskia) located in regions where any future weather modification experiment would be undertaken, and where seeding would be more beneficial to agriculture and water supply needs than in most areas of the state.

The warm season comparisons show similar relations. Thus, the median R/P decreases from 0.21 to 0.10 between all years combined and below-normal years; that is, the percentage of rainfall converted to runoff in dry periods averages less than 50% of that in a normal warm season.

Evaluation of Potential Benefits from Seeding

The net result of our investigation of potential seeding-induced increases in runoff from cloud seeding is that seeding to augment water-supply storage would be desirable in near-normal to slightly below-normal years for those midwestern communities where additional storage is available in such periods. The Illinois calculations indicate that substantial increases in runoff could be achieved in such weather conditions, as. indicated in the condensed summary of Table 35 and other tables and figures throughout this report. The constraints would usually be too great to undertake seeding in above-normal years, the need would rarely exist for additional water supplies, and, seeding to suppress precipitation would be the most frequent need in such weather conditions. The conversion of precipitation to runoff in below-normal years is small, averaging only 10%-13% (Table 35), and large seeding-induced increases in precipitation would be required to obtain substantial alleviation of water-supply deficiencies. This would be difficult to achieve with the atmospheric conditions (unusually hot with low humidities) that exist in moderate to severe drought conditions. The drought problem is further clarified by reference to Table 36 abstracted from Huff and Changnon (1964) which shows frequency distributions of annual R/P ratios for the five basins of Table 35. Thus, only 7% to 10% of the natural precipitation is converted to runoff in a typical 10-year drought, and this percentage lowers to 3% to 5% in 25-year droughts and to a range of 2% to 4% in a 50-year drought.

However, the possibility that seeding may be of assistance during temporary breaks in light to moderate droughts in the Midwest can not be eliminated. This is certainly true where shortages become very acute, in which case even a small contribution from seeding would be usually helpful and economically acceptable. It is certainly possible that increases of the magnitude shown in Table 35 for average conditions in below-normal cold seasons could be helpful (if achievable) under some conditions, especially in small communities where reservoir storage facilities are inadequate or where water is being taken directly from a small stream for municipal usage.

Table 36. Frequency distribution of annual runoff/precipitation ratios (R/P) in 12-month droughts

Basin	R/P for given frequency (years) 10	25	50
Big Muddy	0.07	0.03	0.02
Embarras	0.07	0.03	0.02
Kaskaskia	0.10	0.05	0.03
La Moine	0.08	0.04	0.02
Spoon	0.09	0.05	0.04
Median	0.08	0.04	0.02

Although the investigation of potential seeding-induced increases in runoff from cloud seeding indicated that substantial gains in streamflow could be achieved in near-normal to slightly below-normal years, other studies carried out by the Hydrology Section of the Water Survey indicate that weather modification would not provide a major benefit in water supply in Illinois, unless it could provide substantial additions in relatively severe drought periods. Stall (1965) has shown that, in general, impounding reservoirs in Illinois can withstand a 25-year drought. A few communities would have problems in a drought of 15-year to 20-year frequency, but some could operate in a 50-year drought. Potential benefits from seeding in augmenting shallow groundwater supplies are estimated to be small by groundwater engineers. Hydrologists believe that agriculture would be the primary beneficiary of successful cloud seeding in Illinois.

RECOMMENDATIONS

Studies of the potential for weather modification in Illinois, along with planning for future weather modification experiments, should be concentrated primarily upon agricultural applications. However, additional studies of precipitation conditions during severe droughts are needed to evaluate more realistically the potential for alleviating surface water deficiencies through cloud seeding.

REFERENCES

Changnon, S. A., Jr., and F. A. Huff, 1971: Evaluation of potential benefits of weather modification on agriculture. Final Report, Part I, Contract 14-06-D-6843 (Sponsored by U. S. Dept. of Interior, Bureau of Reclamation, Office of Atmospheric Water Resources), Illinois State Water Survey, Urbana, 77 pp.

Crawford, N. H., and R. K. Linsley, 1962: The synthesis of continuous streamflow hydrographs on a digital computer. Technical Report No. 12, Dept. of Civil Engineering, Stanford University, 12 3 pp.

Giusti, E. V., and M. A. Lopez, 1967: Climate and streamflow of Puerto Rico. Caribbean Journal of Science, Vol. 7, pp. 87-93.

Hudson, H. E., Jr., and W. J. Roberts, 1955: 1952-1955 Illinois drought with special reference to impounding reservoir design. Bulletin 43, Illinois State Water Survey, Urbana, 52 pp.

Huff, F. A., and S. A. Changnon, Jr., 1964: Relation between precipitation deficiency and low streamflow. Journal of Geophysical Research, Vol. 69, No. 4, pp. 605-614.

Leighton, M. M. , G. E. Ekblaw, and L. Horberg, 1948: Physiographic divisions of Illinois. Report of Investigation 129, Illinois State Geological Survey, Urbana.

Lumb, Alan M., and Ray K. Linsley, 1971: Hydrologic consequences of rainfall augmentation. Journal of Hydraulics Div., Proc. Am. Soc. Civil Eng., HY 7, July, 1065-1080.

MacDonald, Gordon, 1966: Weather and climatic modification, problems and prospects. Final Report of Panel on Weather and Climate Modification, National Academy of Sciences-National Research Council, Vol. 2, Publication No. 1350, Washington, D. C.

Smith, Robert L., 1970: Water utilization aspects of weather modification in Kansas. Project Completion Report, Kansas Water Resources Research Institute, Manhattan, Kansas, 50 pp.

Stall, John B., 1962: Soil conservation can reduce reservoir sedimentation. Public Works Magazine, September.

Stall, John B., 1964: Low flows of Illinois streams for impounding reservoir design. Bulletin 51, Illinois State Water Survey, Urbana, 395 pp.

Stall, John B., 1965: Determining yields of impounding reservoirs. Public Works Magazine, September (also, Reprint Series No. 49, Illinois State Water Survey).

Stall, J. B., J. B. Fehrenbacher, L. J. Bartelli, G. 0. Walker, E. L. Sauer, and S. W. Melsted, 1954: Water and land resources of the Crab Orchard Lake basin. Bulletin 42, Illinois State Water Survey, Urbana, 53 pp.

Thornthwaite, C. W., 19 31: The climates of North America according to a new classification. Geographic Review, Vol. 21, pp. 6 33-655.

Von En glen, O. D. , 1942: Geomorphology. Macmillan Company, 1942.

Wischmeier, W. W., and D. D. Smith, 1958: Rainfall energy and its relationship to soil loss. Trans. American Geophysical Union, Vol. 39, No. 2, pp. 285-291.